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DRAFT REPORT

IDENTIFICATION OF FACTORS FOR SELECTING MODES AND ROUTES FOR SHIPPING HIGH-LEVEL RADIOACTIVE WASTE AND SPENT NUCLEAR FUEL

to

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Acronyms

AAR	Association of American Railroads
AASHTO	American Association of State Highway and Transportation Officials
ACE	Radiological accident exposure
AEC	Atomic Energy Commission
ALARA	As low as reasonably achievable
CFR	Code of Federal Regulations
CHP	California Highway Patrol
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
ER	Emergency response
ERDA	Energy Research and Development Administration
FHWA	Federal Highway Administration
FR	Federal Register
GIS	Geographic information system
Hazmat	Hazardous materials
HLW	High-level waste
HMTA	Hazardous Materials Transportation Act
HMTUSA	Hazardous Materials Transportation Uniform Safety Act
HRCQ	Highway route controlled quantity
ICC	Interstate Commerce Commission
IFE	Incident-free exposure

INEL	Idaho National Engineering Laboratory
LLW	Low-level waste
NAE	Non-radiological accident exposure
NRC	Nuclear Regulatory Commission
O/D	Origin/destination
PIH	Poisonous by inhalation
PWR	Pressurized Water Reactor
RAR	Radiological accident risk
ROW	Right-of-way
RSPA	Research and Special Programs Administration, U.S. Department of Transportation
SNF	Spent nuclear fuel
TAG	Technical Advisory Group
TMI	Three Mile Island
TRIS	Transportation Research Information Service
UP	Union Pacific Railroad

Identification of Factors for Selecting Modes and Routes for Shipping High-Level Radioactive Waste and Spent Nuclear Fuel

1.0. Introduction

Section 15 of the Hazardous Materials Transportation Uniform Safety Act (HMTUSA) of 1990[1] directs the U.S. Department of Transportation (DOT) to conduct a study to identify and evaluate factors that should be considered in selecting the modes and routes for transporting high-level radioactive waste and spent nuclear fuel. This report describes the approach and findings of study activities performed in response to this requirement.

1.1. Purpose and Study Approach

The purpose of this study is to meet the requirements of Section 15 of the HMTUSA as it relates to shipments of high-level radioactive waste and spent nuclear fuel. The two principal requirements of this section are to (1) determine which factors, if any, should be taken into consideration by shippers and carriers in selecting routes and modes that, in combination, would enhance overall public safety and (2) assess the degree to which the various factors affect the overall public safety of such shipments.

Several points concerning the direction given by Section 15 are worth noting. First, the emphasis is on *identifying* factors related to public safety. This study, therefore, does not provide a mode or route selection methodology, nor is it a set of selection guidelines. The study focuses on identifying mode and route factors and evaluating their relationship to overall public safety. As such, it may serve as a precursor to developing selection strategies. Cost and economics are not to be used as a basis for identifying and evaluating factors. The benchmark to be used is "overall public safety."

The approach used for this study is illustrated in Figure 1. The organization of this report, described below, follows the steps shown in Figure 1. Appendix A contains definitions of the terms used in this report.

Define Public Safety (Chapter 1.0). The first step was to define "overall public safety" for the purposes of this study. This step was considered crucial because the definition would serve as the basis for the remainder of the study and subsequently guide the evaluation process.

Review Mode and Route Selection Practices (Chapter 2.0). The second step was to provide background for the general topic of mode and route selection in transportation. Industry practice with regard to mode and route selection for general commodities, as well as for hazardous and nuclear materials, was reviewed.

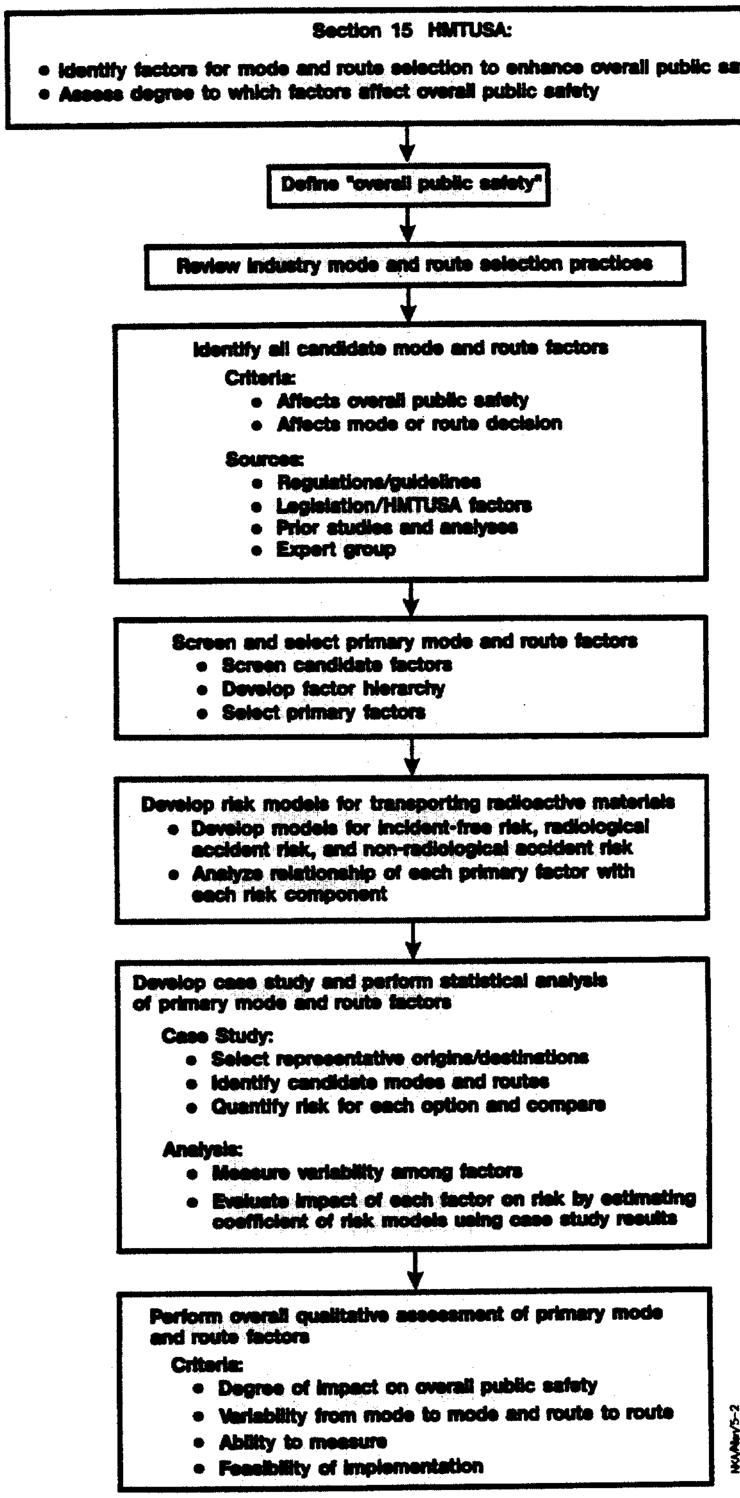

Figure 1. Overall approach to mode and route study.

Identify Candidate Mode and Route Factors (Chapter 3.0). The next step was to develop a comprehensive list of candidate mode and route selection factors. A list was created using the four major sources that were reviewed: existing regulations and regulatory guidelines, legislation (primarily HMTUSA), historical literature, and an expert group assembled for this study. The only criterion used to create the list was that an intuitive relationship should exist between each factor and public safety.

Conduct Qualitative Evaluation of Candidate Factors and Select Primary Factors (Chapter 4.0). Each factor from the comprehensive list was systematically evaluated on the basis of its impact on public safety. A hierarchical framework was used to develop interrelationships among the many candidate factors and to identify a set of primary factors that arguably affect the mode/route choice in the most direct way.

Identify Mode and Route Factors by Modeling the Risk of Transporting Radioactive Materials (Chapter 5.0). Models representing the three components of transportation risk were derived by developing the mathematical relationships of factors considered important in estimating risk. These factors were then compared to the factors selected from the qualitative analysis.

Develop Case Study and Perform Statistical Analysis of Primary Factors (Chapter 6.0). For the primary factors that were readily quantifiable and for which data were readily available, a case study was performed using existing routing and risk assessment models. The factors were measured for representative origin and destination pairs and the variability of the selected factors as modes and routes changed. In addition, their relative impact on public safety was evaluated.

Conduct Overall Assessment of Primary Mode and Route Factors (Chapter 7.0). An overall assessment of each primary factor was conducted using the results of the qualitative evaluation as well as the results of the risk modeling and case study analysis. The criteria used for the analysis were degree of impact on public safety, variability from mode to mode and route to route, ability to measure, and feasibility of implementation.

1.2. Definition of Overall Public Safety

The definition of overall public safety was the benchmark used for this study. Overall public safety is a difficult concept to define because of the many different aspects of safety that can be considered in this context. In absolute terms, overall public safety can be viewed as freedom from danger, injury, or damage. Complete freedom from harm is impossible to achieve and, because the mandate of this study is to identify factors that *enhance* overall public safety, an appropriate working definition had to be placed in a comparative context. With this in mind, the enhancement of overall public safety was defined as:

> *Minimizing exposure from spent nuclear fuel and high-level radioactive waste to the public and the environment during transportation, including ancillary effects. This*

includes minimizing incident-free radiological exposure to the public and to transportation workers and minimizing the potential exposure caused by a radiological release into the environment as a result of an incident during transportation. Enhancement of overall public safety also includes minimizing the impact of accidents during transportation when no radiological release occurs.

Based on this definition, three categories of impact on public safety were considered for the purpose of identifying and evaluating mode and route factors:

1. Incident-free radiological exposure (exposure of both the general public and transport workers that results from normal transportation of radioactive materials)

2. Potential radiological accident exposure (exposure of people and the environment that results from factors affecting both the likelihood and consequence of an accident); the effect of emergency response in minimizing the impact of such potential exposure is explicitly included as a factor that affects the consequences of an accident

3. Potential non-radiological accident public safety impacts (impacts that include traffic fatalities and injuries unrelated to the nature of the cargo).

Incident-free exposure occurs every time radioactive materials are transported. This exposure is generally very small because of regulations that limit the maximum amount of radiation that can be measured outside the container. The related risk is associated with long-term health effects usually expressed in terms of latent cancer fatalities.

Radiological accident exposure is a probabilistic event and is considered a rare occurrence. Such exposure results from an incident during transportation that causes a release of radioactive material. If such a release occurred, the resulting consequences could be greater than those for incident-free exposure, but would still result in health and environmental effects that require some time to manifest themselves.

Non-radiological accident impacts are also probabilistic in nature, but are expected to occur more frequently than release-causing accidents, with more acute health effects at the time of the accident. These health effects include injuries or fatalities resulting from vehicular accidents without a release of radioactive materials.

1.3. Historical Perspective for Mode and Route Selection

As a by-product of the literature review for this study, a synopsis of the history of spent nuclear fuel shipments over the last 40 years was developed. Documents were reviewed to identify significant events that have shaped regulations, carrier practices, and shipper expectations. Figure 2 is a timeline showing significant events in spent nuclear fuel shipping. Events in bold type are directly related to mode and route selection activities. Other events are given for further perspective. After each event, a brief summary of the pertinence of the event is given.

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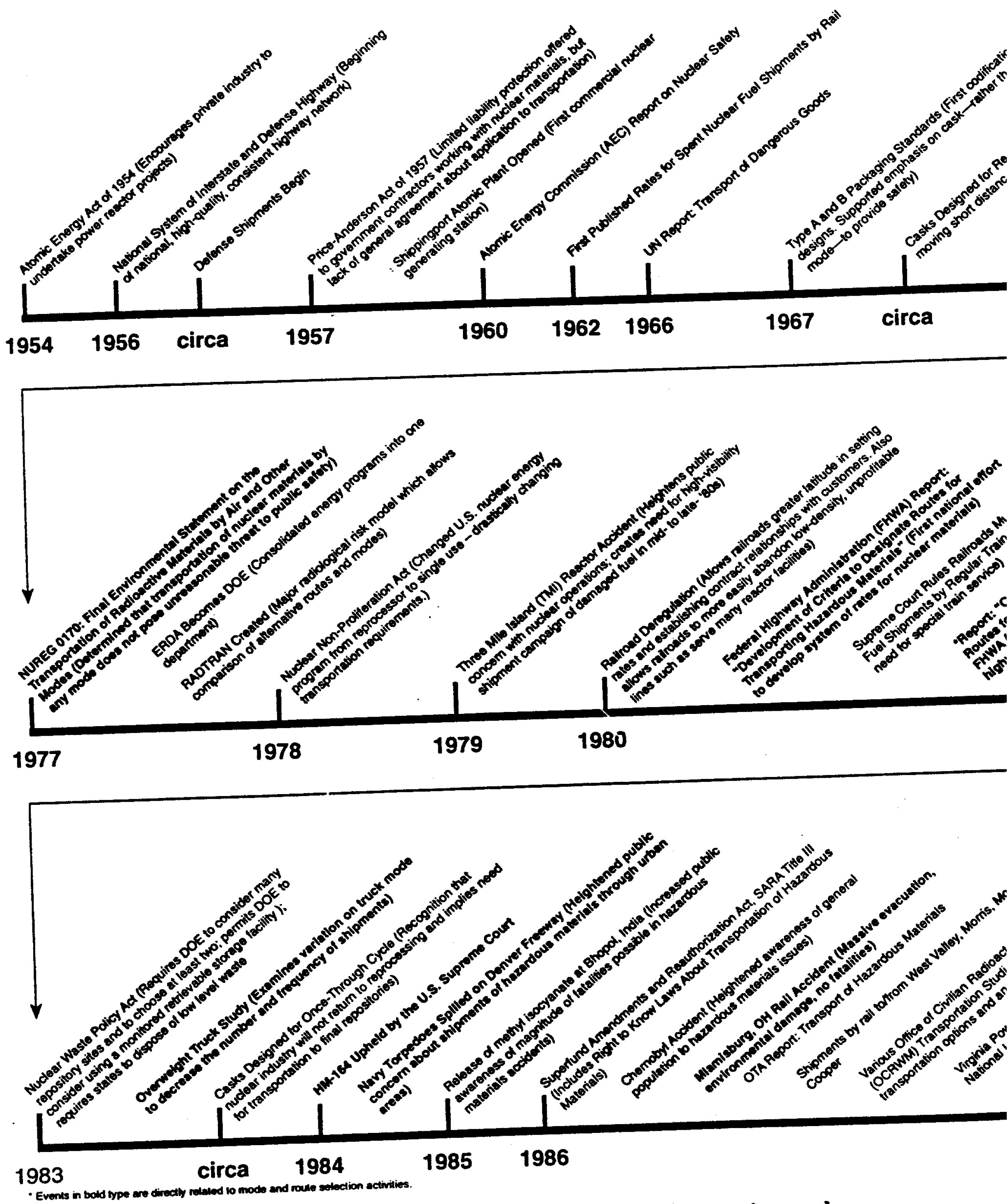

Figure 2. Timeline of significant nuclear and non-nuclear events shaping mode and route options.

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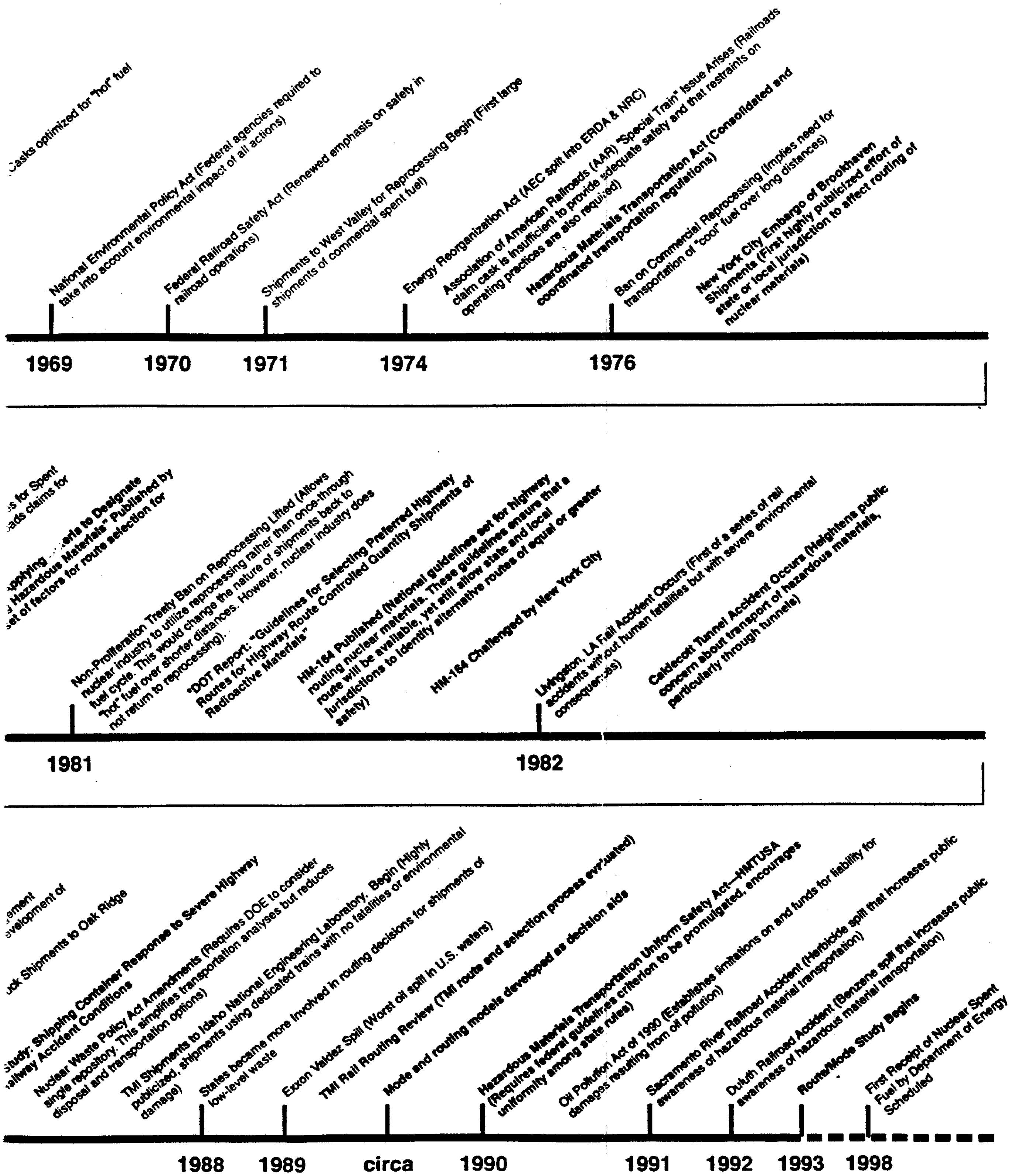

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2.0. Overview of Mode and Route Selection Practices

Shippers and carriers have been selecting modes and routes for general commodities for many years. Their choices are made for a variety of reasons, some of which have changed significantly over the last decade in response to deregulation of transportation modes and general economic conditions.

Shippers also have been making mode and route choices for spent nuclear fuel and other high-level radioactive waste for several decades. Influences on these choices include regulatory requirements and traditional industry practices. The factors that have been considered or proposed in making mode and route choices for both general commodities and hazardous materials are identified in this chapter.

2.1. General Mode and Route Selection Practices

Modal choice and route selection are often directly related. A change of mode will require a change in route (because modes generally do not share rights-of-way); and, conversely, a change in route may require a change in mode. At the same time, some origins or destinations are not served by certain modes. This obviously limits modal choice and routing options.

Historically, modal choices have been made by shippers (the companies sending the products) and routing choices have been made by carriers (the companies moving the products). Also, in the past, regulation has kept carriers from providing services in more than one mode. This distinction has begun to blur in recent years. Deregulation of the transportation industry has allowed carriers to expand into other modes or to develop cooperative arrangements with carriers in other modes. Presumably, carriers are more able to influence—although still not decide—which mode will be used. At the same time, shippers' concerns about service attributes and liability have caused them to seek participation in certain carrier internal activities, such as routing decisions. Additionally, shippers who have a vested interest in a particular mode—perhaps because they own a short railroad, a fleet of trucks, or a fleet of barges—will often choose to use that mode without regard for optimizing modal choice over the short run. Finally, since railroads operate over route structures that they own and control, and some shippers have a choice of several railroads, a shipper's choice of carrier in some cases will essentially determine the route that will be used.

2.1.1. General Mode Selection Practices. Discussions with carriers, shippers, and other persons knowledgeable about these transportation issues and who have worked with hazardous and non-hazardous shipments by highway, rail, and water, revealed that modal choices are made for a variety of reasons.

First and foremost, *shippers can make modal choices only from among those modes that are physically available* to them and their customers. Although almost all businesses are now accessible by highway, fewer have rail service available, and fewer still have waterways available. Further, to complete a shipment, the chosen mode should be available at both the origin and destination. In the case of rail and waterways, this often limits the modal choices available to shippers. This constraint has been somewhat mitigated in recent years by the development of intermodal operations. In intermodal shipments, the product is interchanged one or more times between modes while moving from the shipper to the customer. This allows access to modes that would otherwise be unavailable, although it frequently compromises the size and type of equipment that can be used and requires the commodity and its container to be handled away from the origin or destination.

Second, *shippers choose modes based on various service attributes*. Shippers want to maximize the value of their products by getting them to their customers quickly, without damage, at the lowest possible cost, and in lot sizes convenient to the shipper or the customer. Each of the modes has different abilities to provide speed of transport, frequency of service, and avoidance of damage and to offer low prices, while making a profit for the carrier. Shippers, who have different levels of interest in each of these characteristics based on the nature of their businesses, choose the mode that provides the best combination of service attributes.

Third, *shippers sometimes choose modes to ensure continued availability of a mode or to provide competition among carriers*. For example, a shipper may choose to use highways because of service attributes, but also occasionally makes a rail shipment just to keep a rail line active for possible future use.

Safety is not usually given as the reason for choosing a particular mode. Some observers in the shipping community have noted that all modes are considered safe and that no mode holds a clear advantage, especially for non-hazardous shipments.

These reasons for modal choice are generally supported by the results of a survey of Canadian shippers in the mid-1980s.[2] That study found that shippers choose a particular mode primarily to minimize transit time and generally favor highways for shorter hauls and rail for longer hauls. The study also found that shippers make modal choices based on availability of pickup and delivery services (favoring highway), cooperation between carrier and shipper personnel (favoring highway), and shipment tracing capability (favoring rail). The study further found that in-transit damage (which can be indicative of poor safety performance) is not significant in influencing the choice of any mode.

An earlier survey asked U.S. shippers why they chose a particular mode and a carrier within that mode.[3] The study found that, in general, shippers choose modes based on pickup and delivery services and overall cost. Other selection criteria, in decreasing order of importance, were (1) line haul (ability to serve origin and destination without changing mode or carrier), (2) tracing and expediting, (3) loss and damage, (4) special service and equipment, and (5) sales staff support. This survey was conducted before the transportation modes were deregulated, when carriers' abilities to tailor their services to their customers was restricted. In assessing this survey in the mid-1980s, one of the original authors stated that consistency of service had become "the most important single criterion for evaluating alternatives."[4]

2.1.2. General Route Selection Practices. Analysis, including discussions with carriers, shippers, and other knowledgeable persons, revealed that routing choices are made for a variety of reasons.

Like shippers, *carriers can only choose routes physically available to them*. Even that choice gets complicated for railroads, which, unlike truck companies and barge operators, provide their own rights-of-way. Truck companies and barge operators use highways and waterways that are publicly owned, or, in the case of tollroads and tollbridges, are at least available to the public. Since any company's trucks can use any highway, and since almost all shippers and customers have access to highways, all truck companies are physically able to serve almost all shippers. Similarly, although few shippers and customers have access to waterways, those that have the appropriate facilities can be physically served by all barge companies. There are, of course, regulatory restrictions on locations that some truck companies and barge operators can serve, and some truck companies and barge operators may choose not to serve certain areas.

In contrast, railroad lines are privately owned (with the exception of certain Amtrak routes and State or locally owned rail lines). Service over those lines is controlled by the owning railroad company. Few customers have direct access to more than one railroad. Further, no single railroad company serves more than half of the geographical United States. The need for coordination and cooperation between railroads is clearly essential. For a railroad to provide service over another railroad's tracks, some agreement must be reached between the two. The agreement may be a traditional interchange agreement, where the railroad cars are given to the other railroad and the revenues are divided. Or, it may be a trackage rights agreement, where the owning railroad rents the tracks to the other railroad. These agreements are made in a competitive environment, with each railroad attempting to optimize its own interests. Sometimes those interests result in the owning railroad refusing access to the other railroad. When that occurs, routing options are further limited. Occasionally, railroads may be ordered by the Interstate Commerce Commission (ICC) or the courts to allow access to other railroads to preserve local competition or as a condition of merger or abandonment proceedings.

Beyond the question of physical access, the *private ownership of rail rights-of-way also affects routing*. Railroads generally divide revenues for a shipment based on the proportion of the distance that each railroad hauls the shipment. Each railroad has the incentive, then, to haul the shipment as far as possible before interchanging it to another railroad, even if a shorter haul would result in overall lower costs or shorter time. The railroad that originates the shipment controls where it is interchanged and gets the long haul. Deregulation, and a growing realization that their real competitors are truck companies rather than other railroads, has caused railroads to begin to move away from strict proportional rates in recent years and to focus instead on customer service attributes, even if it means taking the short haul.

Finally, *one additional option of routing is available only to railroads—the ability to embargo their own routes*. In essence, a railroad embargoes a route by placing it out of service to all trains, to those over a certain length or weight, or to those carrying a particular commodity. Embargoes are generally based on temporary conditions (such as the recent flood damage in the Midwest), but can become permanent if a railroad chooses not to make the necessary repairs or upgrades. A recent example is the March 19, 1993, embargo of all hazardous materials shipments on the Long Island Railroad. This embargo was unusual in that it was applied by the Association of American Railroads (an industry group) to an entire railroad, rather than applied by a railroad to a single route. The embargo apparently was based on the condition of track in the freight yards and the danger of sparks from the third rail. (A State official, assessing the situation, noted that spilled gravel from a recent derailment of hopper cars apparently contained a hazardous material. This may have contributed to the decision to impose the embargo.[5]) As a result of the embargo, shippers of hazardous materials were forced to make deliveries and pickups by other modes.

Truck, railroad, and barge companies tend to make routing decisions for the same reason: operational efficiency. Carriers in each mode seek to make best use of their equipment and fixed facilities. For truck companies, this means avoiding long routes, toll roads, States with high fuel taxes, and congested or unreliable routes (perhaps due to weather). For railroads, this means avoiding long routes and congested classification facilities. Railroads also manage their train movements to concentrate traffic on main lines, to accommodate single-track routes, and to utilize efficient schedules and train consists. Barge operators, as mentioned earlier, have very few routing options but, when they do, try to avoid long routes, congested locks, and, to a smaller degree, routes affected by seasonal weather.

2.2. Overview of Mode and Route Selection for Hazardous Materials

2.2.1. Mode Selection for Hazardous Materials. There appears to be little difference in the modal choices made by shippers of hazardous materials and those shipping non-hazardous materials. In fact, most shippers of hazardous materials also transport a large volume of non-hazardous materials and follow the same practices in doing so. Shippers of either hazardous or non-hazardous materials have not typically identified safety as a reason to choose among highways, railroads, or waterways. Generally speaking, from the shippers' perspective, all modes are considered safe and modal choices are made for other reasons, such as cost and convenience. Exceptions include the Department of Defense (DOD) and certain chemical companies that review carrier safety records before making carrier choices. Recently, the concept of exercising "reasonable care" in handling and transporting hazardous materials has caused chemical companies to take an increased interest in selecting modes and carriers based on safety records.

2.2.2. Route Selection for Hazardous Materials. Carriers' routing choices in all modes are affected to varying degrees by Federal, State, Indian Tribe, and local regulations. On their own, most carriers make routing adjustments only for a limited number of hazardous materials. In general, hazardous materials are not differentiated from non-hazardous materials when making routing decisions.

For railroads, however, there has been a modest movement toward changing routing or operating practices in recognition of certain hazardous materials. Telephone calls to several railroads during this study found these examples:

- The Association of American Railroads (AAR) suggests that its member railroads follow Circular No. OT-55-B, which contains operating practices that apply to many hazardous materials. Along with preferred classification yard practices, training requirements for employees who handle cars containing hazardous materials, and support of the TRANSCAER (Transportation Community Awareness and Emergency Response) program, OT-55-B recommends industrywide use of key trains and designation of key routes.

Key trains are trains with 5 or more loaded tank cars containing poisons with an inhalation hazard, or 20 or more carloads or intermodal portable tankloads of a combination of poisons with inhalation hazards, flammable gases, certain explosives, and environmentally sensitive chemicals. Key trains are restricted to a maximum speed of 50 mph, hold the mainline when passing other trains (unless the siding meets FRA Class 2 standards), and may not contain any cars with friction bearings. When a key train is stopped by emergency brake application or unknown cause the train must be inspected for derailed or defective cars. If a defective axle journal is reported by a trackside detector but has no visible defect, the train must be limited to 30 mph until it has successfully passed the next detector. A second failure to pass the detector requires that the car be set out from the train.

Key routes are tracks with a yearly combination of 10,000 carloads or intermodal portable tankloads of hazardous materials or a combination of 4,000 carloads of poisons with inhalation hazards, flammable gases, certain explosives, and environmentally sensitive chemicals. Key routes must have defective wheel bearing detectors no more than 40 miles apart and be inspected by track geometry inspection cars (or equivalent) at least twice each year. Sidings on key routes must be similarly inspected at least once each year. All track where key trains are met or passed must be FRA Class 2 or better.

The key route concept does not stipulate how hazardous materials should be routed, but highlights high-volume routes while ensuring a minimum level of safety detection and inspection equipment.[6]

The AAR recommends that trains moving spent fuel (and certain other forms of radioactive materials) be moved only in special trains. AAR's policy states that:

> Shipments of casks containing irradiated spent fuel cores or empty casks previously loaded with such material should move in special trains containing no other freight, not faster than 35 mph. When a train handling these shipments meets, passes, or is passed by another train, one train should stand while the other moves past not faster than 35 mph.[7]

Neither of these AAR recommendations must be followed by the railroads, but their acceptance often simplifies the interchange of cars and trains between railroads and provides a common basis for the railroads and potential shippers to assess the appropriateness of using rail to transport hazardous materials.

- The Union Pacific railroad system follows the AAR recommendation that key trains be identified and key routes be designated. In implementing the latter concept, the Union Pacific has designated existing routes that carry high volumes of hazardous materials as key routes, but hazardous materials shipments usually follow the same routes that they would if they were not carrying hazardous materials. One exception, which predates the key route concept, is that the Union Pacific routes hazardous material shipments around St. Louis because an equivalent quality parallel mainline is available 100 miles to the east.[8]

In a survey several years ago, the railroad said that it prefers not to route hazardous materials around population centers because doing so often requires using lower quality track.[9]

The Union Pacific does not, however, follow AAR recommendations to use special trains for radioactive shipments and instead follows its own operating rules or accommodates customer requests for handling. Generally, the Union Pacific will carry radioactive materials in regular trains although recent radioactive shipments for the Department of Defense (DOD) have been handled in dedicated trains restricted to 35 mph (at DOD's request). Spent fuel shipments from Three Mile Island have been handled in dedicated trains restricted to 50 mph (based on negotiations with the DOE and other interested parties).[8]

- The Norfolk Southern follows the AAR's key train recommendations for certain hazardous materials and the AAR's special train recommendations for spent fuel casks.[10]

- Conrail follows AAR key train recommendations for hazardous materials and AAR special train recommendations for spent fuel casks.

  In addition to following the AAR's special train recommendations for spent fuel casks, Conrail also accommodates requests for advance notification of shipment by States, Indian Tribes, and local jurisdictions. Conrail also prefers to route trains carrying spent fuel on main lines whenever possible.[11]

2.3. Overview of Regulations Affecting Mode and Route Selection

Various Federal, State, Indian Tribe, and local governmental agencies have authority to regulate transportation. Sometimes State, Indian Tribe, and local agency regulations are overridden by Federal regulations; and sometimes Federal, State, Indian Tribes, and local agencies choose not to exercise the authority that they have been given.

2.3.1. Regulation of Mode and Route Selection for Non-Hazardous Materials.

Mode Selection. No *Federal, State, Indian Tribe, or local* regulation requiring the use of a particular mode for non-hazardous materials could be identified as a result of a detailed review of regulations.

Route Selection. No *Federal* regulations that address the routing of non-hazardous materials could be identified. The U.S. Coast Guard does have authority to suspend navigation on a particular waterway due to seasonal conditions or emergencies. This could cause a rerouting or change of mode; but, because of the limited route options available to barge companies, these closings are more likely to cause a delay or change of mode than a change in route.

State, Indian Tribes, and local jurisdictions take a variety of approaches to regulating, or at least influencing, routing of highway shipments. Those jurisdictions routinely restrict trucks from operating on certain highways by imposing weight and clearance limits. These limits reflect the design or condition of the infrastructure and are intended to prevent damage or excess wear to the surfaces and structures. Truck routes are also designated through many cities to keep trucks on highways considered more suitable to that type of vehicle or to avoid residential neighborhoods and other selected locations. The criteria for designating these truck routes vary from jurisdiction to jurisdiction and, in some cases, are extended to exclude trucks from parkways and other auto-only roadways.

Finally, some jurisdictions impose curfews on hours of truck operation on certain roads or in certain areas of a city. Those curfews are either for noise abatement or to alleviate congestion. Waivers and exceptions to all these restrictions are granted with varying degrees of regularity.

2.3.2. Regulation of Mode and Route Selection for Hazardous Materials.

Mode Selection. No *Federal, State, Indian Tribe, or local* regulations that require the use of a particular mode for hazardous materials could be identified as a result of a detailed review of regulations. Some regulations prohibit carrying specific materials by certain modes, however. One example is ethylene chloridrin, which is not permitted in rail transportation by Title 49, Code of Federal Regulations, Section 173.223 (49 CFR 173.223).

Route Selection. Generally speaking, the commodity being shipped does not affect the routing choice made by the carriers in any of the modes. Exceptions include explosives; combustibles; certain other hazardous materials that are prohibited from some tunnels, bridges, and highways by State or local regulation; and highway-route-controlled quantities of radioactive materials. The governmental routing regulations frequently apply only to hazardous materials passing through a locality; pickups and deliveries are routinely exempted from the restrictions.

Various Federal, State, Indian Tribe, and local agencies have jurisdiction over aspects of hazardous materials routing on highways. Authority over hazardous materials routing is complicated by overlapping jurisdictions and issues of interstate commerce.

Federal. The Hazardous Materials Transportation Act (HMTA) provides DOT with the authority to regulate the routing of hazardous materials shipments. For many years, the Federal Highway Administration (FHWA) had the only regulation that prescribed routing restrictions for hazardous materials. Section 397.9 of the Federal Motor Carrier Safety Regulations states that "Unless there is no practicable alternative, a motor vehicle which contains hazardous materials must be operated over routes which do not go through or near heavily populated areas, places where crowds assemble, tunnels, narrow streets or alleys," but gives no specific definitions for when these restricted conditions exist.

In 1981, the DOT published a set of routing guidelines for hazardous materials to be used by State and local agencies. These guidelines were most recently updated in 1989.[12] The guidelines are not mandatory, but have been used by many agencies. The Federal Highway Administration is currently promulgating new hazardous materials routing regulations as directed by the Hazardous Materials Transportation Uniform Safety Act (HMTUSA) of 1990.[13]

DOT also issued regulations in 1982 that prescribe routing requirements for certain quantities of radioactive materials (49 CFR 173.22 and 177.825). These regulations are generally referred to by their original docket number, "HM-164."[14] The regulations require that carriers follow "preferred routes," which are interstate highways, and/or any other route designated by a State routing agency. Carriers are instructed to choose a preferred route to reduce travel time and to use urban bypasses where available. DOT also has published a set of guidelines to assist State agencies and Indian Tribes in designating routes that satisfy HM-164.[15] There are no comparable U.S. DOT regulations or guidelines for rail or water shipments.

The Nuclear Regulatory Commission (NRC) also has authority to regulate highway routing of certain types of radioactive materials to ensure adequate security. A Memorandum of Understanding between DOT and the NRC stipulates that each agency will coordinate any radioactive materials transportation regulations developed by the other.

State and Indian Tribes. A survey by the American Association of State Highway and Transportation Officials (AASHTO) found that 22 of 46 responding States have some form of routing authority over hazardous materials shipments.[9] The presence of routing authority does not necessarily mean that the States are exercising that authority. Several States are considering expanding or implementing routing authority over hazardous materials shipments. In general, States regulate hazardous materials routing by prohibiting the use of certain routes rather than designating acceptable routes.[9] Indian Tribes can invoke authority over routing in the same manner as States for shipments through their jurisdictions.

California is one of the few States that regulate explosives routing. The State has designated a network of approved routes with enforcement by the California Highway Patrol (CHP). California has also established a network of routes for hazardous materials that are poisonous by inhalation (PIH materials).

Because the Federal government has promulgated highway routing requirements for radioactive materials, States and Indian Tribes have often focused instead on ancillary transportation regulations, such as notification requirements, inspection, and escorts. Some of the truck and cask combinations used to transport spent nuclear fuel and high-level nuclear waste exceed State and Indian Tribe highway weight limits. As such, they usually require special permits and are restricted to using certain highways. These restrictions are due to the total weight of the loaded truck, rather than the nature of the commodity being transported.

Several States have taken advantage of the provisions within HM-164 and have designated alternative routes for spent nuclear fuel shipments. The routes are in place of, or in addition to, the base HM-164 network of interstate highways and urban bypasses.

Local. The AASHTO survey found that local agencies exercise hazardous materials routing authority in 19 of 46 States. In seven of the 19 States, the local agencies exercise routing authority over all roadways, including State highways. The authority in each State, and the degree to which that authority is exercised, varies widely. In Washington, for example, local agencies have complete authority to prohibit hazardous materials on all roadways under their jurisdiction. In California, local agencies can regulate hazardous materials routing, subject to review by the CHP.[9] In that State, a routing restriction must

1. Apply only to highways appreciably less safe than alternatives
2. Not be preempted by Federal regulation
3. Not eliminate access to pickup and delivery points or necessary service
4. Preserve at least one legal alternative route.

Columbus, Ohio, has implemented a type of routing restriction that is gaining popularity in the Midwest. The city requires that all through shipments of hazardous materials must use an outerbelt interstate highway around the city, even if total mileage and time is increased. "Hazardous Cargo" routes are posted and exceptions require permits from the Fire Chief.[16] The restriction was prompted by the overturn of a truck carrying hydrogen peroxide at the downtown interchange of the two main interstate highways in the late 1980s.

Local agencies are generally not involved in routing radioactive materials, although they have, on several occasions, attempted to impose routing regulations that were later overturned or preempted. The most notable case was New York City's attempt to prevent shipments of spent nuclear fuel moving off Long Island through the city. New York City's attempts to block these shipments raised the question of how to involve State and local jurisdictions in radioactive material shipments and resulted in the promulgation of HM-164.[17] Another example is the proclamation by certain municipalities that they are "Nuclear Free Zones" in which no radioactive materials can be handled, processed, stored, or transported. More than 100 cities have declared themselves Nuclear Free Zones, including Takoma Park, Maryland; Chicago, Illinois; and Oakland, California. Court cases have decided that these declarations do not have the force of law. The designations, however, indicate a community's opposition to nuclear transportation and could, in certain cases, influence routing decisions.[18]

There are no known local routing requirements for radioactive materials shipments by rail or waterway.

3.0. Identification of Candidate Mode and Route Factors

Mode and route decisions historically have not been based on safety criteria. The criteria these decisions have been based on were reviewed in Chapter 2.0. The purpose of this chapter is to focus on criteria directly related to "overall public safety," as defined in Chapter 1.0.

The first step in the effort to identify the most important safety factors for mode and route selection was to develop a comprehensive list of candidate factors. These factors were then carefully screened and evaluated and ultimately narrowed down to a set of primary mode and route selection factors for more detailed assessment. Chapter 3.0 describes the process for identifying mode and route factors. Chapter 4.0 then describes the manner in which the candidate factors were evaluated and prioritized.

3.1. Enumeration of Factors

A comprehensive list of candidate mode and route factors was compiled using the project definition of overall public safety as a guide. Minimal constraints were used in developing the list other than a factor's intuitive relationship to public safety. In the initial compilation, no effort was made to organize the factors or to group them in any way. This allowed the project team to compile the list without bias or reference to existing procedures.

The factors were collected from several sources including (1) current regulations and regulatory guidelines, (2) HMTUSA, (3) a historical review of archival literature, (4) a Mode/Route Technical Advisory Group (TAG) convened for this study, and (5) project team expertise. All identifiable factors contained in current regulations and published documents were added to the list without reference to the route selection procedure or risk assessment technique. This was considered important because shippers and carriers are generally familiar with current regulatory guidelines and operate with these factors and procedures in mind.

The TAG was convened specifically to act as an expert panel for this study. The group represented broad interests including carriers; shippers; local, State, and Federal governments; public interest groups; and regional energy groups (see Appendix B). The members were provided the list of factors prior to the meeting and at the meeting were asked to provide input on additions or changes to the initial comprehensive list, as well as guidance on representative units of measure and ability to measure the factors.

3.2. Guidelines for Routing Hazardous Materials

Federal regulations governing the routing of hazardous and radioactive material were mentioned in Section 2.3.2. It was noted that the U.S. DOT has prepared guidelines for States and other jurisdictions to use when designating routes for both general hazardous materials and for highway route controlled quantities of radioactive materials. In addition, Transport Canada has developed a set of hazardous materials routing guidelines for shipments in Canada.[19] Regulatory guidelines are an important source of candidate mode and route factors, though it is recognized that these guidelines were prepared for use by State routing officials and not for use by shippers and carriers, who are the focus of this report. Because of the importance of regulatory guidelines, it is worthwhile to provide some background on the methodology and criteria they employed.

3.2.1. DOT Hazardous Materials Routing Guidelines. DOT's hazardous materials (hazmat) guidelines are based on the concept of relative risk. That is, only those factors that are potentially different between alternate routes are considered in the risk assessment that forms the basis for the route decision. Risk is measured using two primary factors:

1. The expected, per-mile population exposure to a release (population risk)

2. The expected, per-mile property value exposure (property risk). (The estimation of property risk is considered optional in the route selection process.)

These two primary factors are computed for each route, but are not combined in any way. Population risk is estimated using accident rate and population density information. Property risk is also estimated using accident rate information, but considers property values instead of population density.

The DOT guidelines suggest that accident rate information be obtained from the best possible information source. DOT suggests that, when available, the analyst should use accident rates that are based on the most severe accidents (such as fatal accidents). This is in recognition of the fact that many accidents are not severe enough to cause a release of hazardous materials from containers. A simple regression model, based on the average daily traffic volume of each interstate route segment, is also provided for estimating accident probabilities.

Population density information along each route is necessary to estimate the number of people that would be at risk during an accidental release. The approach recommended in the guidelines is to use census tract data to estimate the fraction of the population along a route within the release impact zone. The choice of bandwidth along each route is based on the suggested evacuation distance of the nine classes of hazardous materials.

Property value is estimated by measuring lineal frontage and its value along each route. The release impact zones that are important in the population risk assessment process are not used in the property risk assessment process.

Route selection is based on the primary risk factors (population and property risk) and on subjective factors. If the primary risk factors for multiple routes are so close that a definitive decision cannot be made, the secondary subjective factors are employed. Decision makers use the secondary subjective factors to differentiate close calls.

Four types of secondary subjective factors are considered in the guidelines:

1. Special populations located in facilities that are difficult to evacuate (nursing homes, schools, hospitals)

2. Special properties (utilities, transportation bottlenecks, difficult-to-reach facilities)

3. Emergency response capability

4. Other subjective factors of special interest to a community.

The types and quantities of these secondary factors are listed for each route. There is no attempt to analytically combine these factors.

The primary and subjective factors from the DOT hazardous materials guidelines are shown in Table 1. Each of these factors is broken down into more specific factors in the second column and measureable components in the third column.

3.2.2. DOT Routing Guidelines for Highway Route Controlled Quantity Shipments of Radioactive Materials. These DOT routing guidelines provide a methodology for States and other jurisdictions to use when determining the lowest risk route for the transport of highway route controlled quantity (HRCQ) radioactive materials. "Highway route controlled quantity" is a term specifically defined in the Federal Hazardous Materials Regulations, (49 CFR 173.403).

The methodology used in the guidelines is to develop a "figure of merit" for each route considered. This figure represents the comparative risk between routes; it is not a measure of absolute risk. Each figure of merit is developed based upon three primary risk factors: normal radiation exposure, public health risk from accidents, and economic risk from accidents (see Table 1).

Normal radiation exposure refers to the amount of radiation emitted during normal, or incident-free, transportation operations. An equation is used to calculate the normal radiation exposure factor. This equation includes the following components: average population density, length of route, vehicle speed, and average traffic count.

Public health risk from accidents refers to the potential number of people exposed if a transportation accident were severe enough to lead to a release of the radioactive materials from the transport container. Risk from accidental release of radioactive materials depends on two factors:

1. The frequency of accidents that could result in release

2. The consequence from such accidents, in terms of the number of people that could be exposed to radioactive materials if a release occurs.

Accident release frequencies are calculated by multiplying the accident rate by the route or route segment length. Packages containing HRCQ radioactive materials are required by DOT and NRC regulations to retain their contents even in very severe accidents. Consequently, the guidelines suggest the use of accident rates that represent the most severe accidents involving the types of vehicles expected to carry HRCQ. The most appropriate would be the fatality rate for drivers of vehicles containing hazardous materials. Since this level of specificity in accident rates is usually not available, DOT provides a rank preference list for the types of accident rates that could best represent accident release frequencies.

Table 1. Factors in routing guidelines developed for use by State and local governments.

Generic Factors	Specific Factors	Measurable Components
	U.S. DOT Hazmat Guidelines	
Primary Factors:		
Relative Population Risk	Accident Probability	Accident rate
	Population Potentially at Risk	Population within "impact" zone (depends on hazard class)
Relative Property Risk	Accident Probability	Accident rate
	Property Potentially at Risk	Property value of lineal frontage
Subjective Factors:		
Special Populations	Type of Special Populations (schools, hospitals, etc.)	Number along route
Special Properties	Types of Special Properties (utilities, structures, etc.)	Number along route
Emergency Response	Emergency Response Facilities	Proximity to route segments
Other	As identified by the community doing the analysis	
	U.S. DOT HRCQ Guidelines	
Primary Factors:		
Normal Radiation Exposure	Population Potentially Exposed	Population with 0-5 mile band; Transport workers (drivers, handlers, etc.); Passengers in other vehicles; People at stops
	Travel Time	Shipment distance; Vehicle speed
Public Health Risk from Accidents	Accident Release Consequence	Population within 0-5 mile band, and; Population within 5-10 mile band
	Accident Release Frequency	Accident rate
Economic Risks from Accidents	Accident Release Consequence	Types of property within 0-5 mile band; Types of property within 5-10 mile band
	Accident Release Frequency	Accident rate
Secondary Factors:		
Emergency Response	Response Time; Equipment Availability; Training; Manpower Availability; Type of Land Use	None—Subjective scaling
Evacuation	Population Density; Egress Availability; Manpower/Equipment; Evacuation Time; Evacuation Impacts; Land Use Type	None—Subjective scaling
Special Facilities	Dose Response; Accident Evacuation; Economics; Type of Facility	None—Subjective scaling
Traffic Fatalities and Injuries	Fatalities and injuries	Accident rate
	Canadian Route Screening for Dangerous Goods by Highway	
Population Risk	Population Potentially Exposed	Population within impact area
	Accident Probability	Accident rate
Property Risk	Property Potentially Exposed	Property within impact area
	Accident Probability	Accident rate
Environmental Risk	Sensitive Environments Potentially Exposed	Sensitive environments within impact area
	Accident Probability	Accident rate
Emergency Response	ER Capability	Number of units within 10 minutes

Accident release consequences depend on a number of factors, many of which (such as atmospheric conditions and type of material transported) would be similar for two alternate routes. This greatly simplifies the calculation of consequences to a consideration of the differing levels of population along the route or route segment.

Economic risk from accidents refers to the potential contamination of property near the roadway that could result if a transportation accident were to occur. The cost of removing contaminated property would vary widely based on the type of property adjacent to the roadway. To determine the risk, the type of property along the route segment is classified as rural, residential, commercial/ industrial, park, or public area.

If an analysis of the primary factors does not indicate a clear choice for the lowest risk route, secondary factors may be considered. These include emergency response, evacuation potential, special facilities, and traffic fatalities and injuries.

A summary of the primary and secondary factors for the HRCQ guidelines is presented in the middle portion of Table 1. Again, these factors are further broken down into more specific elements and measureable components for each of these elements.

3.2.3. Canadian Route Screening Guidelines for Dangerous Goods by Truck. The Canadian route screening guidelines provide the Canadian national approach for routing hazardous materials (dangerous goods). This methodology is similar to the current U.S. DOT hazardous materials routing guidelines, but it puts greater emphasis on emergency response and environmental impacts to make the final routing decision. Overall, four major factors are identified to help select routes: population risk, property risk, environmental risk, and emergency response. This is shown in the lower portion of Table 1.

The routing method relies on three major inputs: (1) accident probability, (2) accident consequences, and (3) emergency response capabilities. Accident consequences are further subdivided into population, property, and environmental exposure.

Accident probabilities are composed of accident rate data and length of route segments. Consequences are estimated assuming a 2-kilometer corridor width of exposure (other corridor widths can be input). Reference data are provided to help quantify population, property, and environmental exposure. Emergency response capability is defined as the number of qualified response units that could respond to the accident in 10 minutes divided by the length of the relevant route segment.

Routes are screened using the lowest level of analytical detail to eliminate those routes that are clearly not suitable. This screening includes consideration of physical and legal constraints to hazardous material transport. Once the number of potential routes has been reduced to a manageable size, a more detailed analysis is performed. The final selection of a route is made in either of two ways. In one method, each route receives a single risk number that translates various risk assessment elements into one number (the route with the highest number is preferred). The other method is to stop short of this final translation and present the major assessment attributes in a tabular form, then allow the decision makers to apply subjective judgment.

3.3. Candidate Mode and Route Factors Identified in the HMTUSA

HMTUSA contains several provisions that relate directly to mode/route selection criteria. First, as discussed in the introduction, Section 15 requires conducting a mode and route study. Congress specifically includes a number of factors that DOT is to consider (see Table 2). Second, Section 4 of HMTUSA directs DOT to establish Federal standards for the States and Indian Tribes to use to designate routes. (The FHWA is currently promulgating this rule, as previously mentioned.) Congress also includes a list of factors that DOT is to consider for this rulemaking. These factors are also shown in Table 2 and were included in the comprehensive list of factors developed for consideration in this study.

Table 2. Potential mode and route selection factors identified in HMTUSA.

Section 4—Highway Routing Standards Rulemaking Requirements
Population density
Type of highways
Type and quantities of hazardous materials
Emergency response capabilities
Results of consultations with affected parties
Exposure and other risk factors
Terrain considerations
Continuity of routes
Alternative routes
Effects on commerce
Delays in transportation
Section 15—Mode and Route Study Requirements
Population density
Types and conditions of modal infrastructures (such as highways, railbeds, and waterways)
Quantities of high-level waste and spent nuclear fuel
Emergency response capabilities
Exposure and other risk factors
Terrain considerations
Continuity of routes
Available alternative routes
Environmental impact factors

3.4. Candidate Mode and Route Factors Identified in the Literature

An extensive literature review was conducted to identify factors that carriers, shippers, and other interested parties have identified as being particularly important in selecting a mode and route to improve safety. Over 200 documents were reviewed. Documents were chosen by consulting with DOT staff, other Federal and State agencies, the TAG established for this study, and carriers and shippers, as well as by searching the Transportation Research Information Service (TRIS). A bibliography of pertinent documents reviewed by the project team is given in Appendix C.

The documents reviewed for this project can be categorized as follows:

- Modal studies
- Routing studies/evaluations
- Risk assessments
- Environmental assessments
- General hazardous material transportation studies.

Obviously there is considerable overlap of some documents across these categories.

Table 3 represents a comprehensive list of every potential factor identified from the review of past studies and documents as important for route and/or mode selection. Only minor editing has been done from the initial raw list of factors drawn from the literature review. For example, obvious redundancies were eliminated. Some of the factors appeared in many documents, while others appeared in only one or a few documents. No attempt was made to weight their importance by the number or type of document in which the factor was considered. No importance is implied by the order of presentation in Table 3.

The project team was careful not to prejudge the validity of factors during the literature review. The factors were included in the comprehensive list regardless of their source. Many of the source documents were technical studies in which a few mode or route factors were evaluated in great detail. Other documents treated factors in a more summary fashion. A number of the documents reviewed were actually reports on the results of public meetings or were reports that incorporated public input. As such, the list represents a broad cross section of viewpoints.

Table 3. List of factors identified during literature review that have been evaluated or proposed as key issues for mode and/or route selection.

- Population at risk
- Length of shipment
- Community "safety index"
- Classification of highway, railway, or waterway
- Grade of highway or railway
- Separation of traffic
- Accident likelihood
- Tradeoff between risk and travel time
- Population density
- Number of crossings or intersections
- High accident locations ("hot spots")
- Local viewpoints
- Worker population at risk
- Cask design and fabrication
- Emergency response
- Tradeoff between population centers and circuitous routes
- Train stops per trip
- Stop times
- Train speed between terminals
- Posted speed limits by route/mode
- System elasticity/recoverability
- Train crew exposure
- Track profile
- Exposures during train stops to crew and surrounding population
- Track or road curvature
- Run-through (dedicated) vs. classification trains
- Shipment duration
- Amount of other hazmat traffic along mode/route
- Wayside detectors along rail routes
- Exposure to escorts and responders
- Movement control, signalization, etc. by mode
- Carrier communication/tracking capability
- Hiring practices and training by carrier/mode
- Substance abuse programs (vary by mode/carrier)
- Sabotage and vandalism (vary by mode)
- Quantity of material to be shipped and cask capacity (causes number of shipments by mode to vary)
- Population brought into contact
- Non-occupation exposure to persons beside the right-of-way (off-link dose)
- Exposures during highway stops (truck stops, etc.)
- Low probability/high consequence accident potential
- Time of day for shipment
- Distance of crew from packagings
- Distance of population from shipments
- Configuration of shipment (dedicated vs. regular train, single vs. truck convoy, etc.)
- Escort requirements by mode
- Percent of travel in population zones (urban, suburban, rural)
- Non-radiological impacts such as regular accidents
- Radiological impacts from accidents
- Number of waste shipments
- Vehicle speed
- Quality control by carrier
- Human error potential
- Equipment exchanges enroute
- Number of inspections (may vary by mode and route)
- Exposure to others sharing same route (on-link exposure)
- Stop time/delays at origin and destination rail terminals
- Origin/destination
- Need to pick up or drop off cars enroute
- Work rules/union procedures (vary by carrier/mode)
- Proximity of emergency responders
- Communication capability of responders
- Equipment availability/replacement for emergency response
- Ability to restore to normal after response to accident
- Total number of stops enroute
- Number of handling railroads
- Incidence of classification
- Level of enforcement (varies by route or mode)
- State licensing requirements
- Carrier shipment monitoring capability
- Weather/wind conditions (differ by route location)
- Visibility conditions enroute
- Cask size limitations (weight, height)
- Degree of cooperation with jurisdiction along route
- Person exposure

3.5. Comprehensive List of Candidate Factors

The factors identified from regulatory guidelines, legislation, and the literature review were consolidated into a comprehensive list of potential mode and route factors. Before this could be done, the raw lists had to be edited to eliminate redundancies and anomalies. First, there was some duplication of factors from one list to another (Tables 1, 2, and 3). For example, "population density" is listed as a factor on Tables 2 and 3. Second, a number of factors could be combined into one representative factor. For example, "population at risk," "exposure," "population density," and "population brought into contact" all relate to population subject to exposure. "Population" was used as the representative factor for all of these in the comprehensive list and was then broken down into its various components (residential, occupational, etc.).

Finally, several "factors" in Table 3 were either so general in nature or combined several discrete factors in such a way that they had to be decomposed into factors that could be measured and compared with other factors. Examples include

- Tradeoffs between population centers and circuitous routes
- Low-probability/high-consequence accident potential
- Run-through vs. classification trains
- Configuration of shipments
- Stop time/delays at origin and destination terminals.

The net result of the editing process was a single comprehensive list of 82 potential mode and route factors. The factors were organized into eight general categories to facilitate the initial evaluation by the Technical Advisory Group (see Chapter 4 for more on this group). These factors and categories are shown in Table 4 along with an example to further illustrate each factor.

Table 4. Comprehensive list of candidate factors.

Category/Safety Factor	Example
Population and Environment	
Occupational: on-board	Crew on vehicle
Occupational: support	Handling, security, interchange
Public: residential	People at home
Public: non-residential	People at work, tourists
Public: shared-facility users	Other traffic on route, at stops
Public: special populations	Hospitals, schools, arenas, prisons
Sensitive environment	Wetlands, refuges, reservoirs, tribal sacred grounds
Transportation Infrastructure and Utilization	
Functional classification	Arterial, collector, local or class 1, class 2
Opposing traffic separation	Median or two tracks
Grade	Uphill or downhill
Curvature	Curve in alignment
Crossings	Intersections, rail crossings, river confluences
"Hot Spots"	Known problem areas
Accident likelihood	Number of accidents per mile along route or by mode
Posted speed	Speed limit
Route length	Distance for mode
Clearance/weight limitations	Bridge clearances, channel depth
Traffic density	Vehicles per length per lane
Maintenance	Upkeep of roads or rails or channels
Accident rate and severity	National or local accident statistics
System elasticity	Ability to resume normal conditions after an incident
Travel times/delays	Congestion
Structural impediments	Light poles or guardrails
Hazmat traffic density	Density of other hazmat vehicles
Wayside detectors	Hotbox, dragging equipment
Available detours	System rerouting of traffic
Operating Procedures	
Time of day	Rush hour conditions
Operating speed	Controlled speed
Number of stops	Rests or sidings for other traffic to pass, refueling, locks and dams

Table 4. Comprehensive list of candidate factors (continued).

Category/Safety Factor	Example
<u>Operating Procedures</u> (Continued)	
Stop times	Average time of stops
Crew distance from cask(s)	Locating crew on vehicle
Configuration	Dedicated vs. manifest, convoys, other hazmat
Escorts	Chase vehicles, ER, armed guards, medical
Interchanges	Changing rail companies, cornfield vs. gateway
Classifications	Rail yard classification
Handlings	Casks are loaded/unloaded on vehicle
Equipment changes in route	Changing engines
Inspections	Checking equipment at stops
Origin/destination	Beginning and ending of route
Pick up/drop off in route	Adding vehicles from sidings
Work rules	Hours for driver operation
Available alternatives	Other routes or modes available to serve O/D
<u>Emergency Response (ER)</u>	
Proximity/accessibility	Location of ER with respect to route
Capability	Ability to respond to nuclear waste accident
Evacuation potential	Can surrounding population be evacuated
Communication	Remote computer, fax links
Equipment replacement	Availability of equipment (rail cars, tractor trailers)
Restoration to normal operations	Time for normal activity to resume
Medical care	Type of care for radiation exposure
Response times	Time to provide effective response
Training	Quality and amount of training for ER
Available manpower	Number of available responses
<u>Quality Control</u>	
Movement control	Signalization
Communication	Procedure for contacting vehicle
Training	Driving, emergency, handling
Hiring practices	Driver experience, previous driving record
Enforcement	Company procedures
Dispatching	Hours of operation
Vehicle maintenance/inspection	Company procedures

Table 4. Comprehensive list of candidate factors (continued).

Category/Safety Factor	Example
<u>Quality Control</u> (Continued)	
Licensing	State procedures
System monitoring	Ability to track vehicle
Substance abuse enforcement	Monitoring for substance abuse
Sabotage and vandalism	Obstructions on right of way (ROW), destruction of signs and signals
<u>Weather/Climate Terrain/Conditions</u>	
Seasonal road conditions	Snow or sleet, hot or cold
Terrain	Mountainous, hilly, flat
Wind speed, direction, stability	Wind conditions for dispersal
Visibility	Fog, dust, fires
<u>Shipment Characteristics</u>	
Waste type and level of radioactivity	Age and type of nuclear waste
Number of waste shipments	Number of shipments per time
Quantity per shipment	Size of shipment
Cask capacity	Size of cask
Release rates	Non-accident material release
Cask availability	Type and size of cask
Cask size limitations	Physical constraints (weight, length, etc.)
<u>Regulation and Other Restrictions</u>	
Cask design and fabrications	Type of cask
Legal restrictions	Existing legal restrictions due to overweight, oversize, or hazmat
Time of day restrictions	City blackouts (no-travel times)
Jurisdictional cooperation	State-Federal cooperation
Continuity of routes	Continuous route for carrier
Effects on commerce	Increased transit times
Consultations with affected parties	Discussions with surrounding communities
Community Safety Index	Subjective rating of local conditions

4.0. Qualitative Evaluation of Candidate Factors and Selection of Primary Mode and Route Factors

Screening and evaluating the comprehensive list of candidate mode and route factors led to the identification of a set of primary factors. This chapter reviews the screening process and the results of the evaluation of candidate factors.

4.1. Screening of Comprehensive List of Factors

The purpose of the screening process was to begin to narrow down the number of candidate mode and route factors so that, ultimately, the most important factors could be identified.

Key considerations in the screening process included (1) a factor's relationship to the project definition of public safety, (2) the extent to which a factor could affect mode or route choice, (3) interdependencies among factors, and (4) the extent to which candidate factors can be measured and implemented. A factor may be closely related to safety, yet its importance is diminished if it cannot be effectively measured or would be difficult or infeasible to implement as decision-making policy. These criteria were applied to each factor within every functional group on the comprehensive list.

4.1.1. Technical Advisory Group. A Mode/Route Technical Advisory Group (TAG) was convened for this study to assist in reviewing and screening the comprehensive list of factors. The group consisted of representatives from most sectors that have an interest in the selection of mode and route factors for transporting high-level radioactive waste and spent nuclear fuel. Representatives were invited from the following sectors:

- Highway carriers
- Rail carriers
- Water carriers
- Nuclear shippers
- State/local governments
- Tribal governments
- Regional State groups
- Regional energy groups
- Public interest groups
- Federal agencies.

Federal agencies that were invited to participate included the U.S. DOT (including the Research and Special Programs Administration, FHWA, FRA, and the U.S. Coast Guard), the Nuclear Regulatory Commission, the Nuclear Waste Technical Review Board, and the U.S. Department of Energy (DOE). The individuals and organizations participating in the TAG are identified in Appendix B.

The purpose of convening the TAG was to gather viewpoints from as broad a spectrum as possible. A consensus on selection of mode and route factors was not envisioned, given the wide difference of backgrounds and positions of the members. The goal was for the TAG to assist in the screening process by reviewing the comprehensive list of candidate factors and making recommendations on the relative importance and applicability of each factor.

4.1.2. TAG Meeting and Review of Factors. The TAG met for one day in Chicago, Illinois, on May 18, 1993. Prior to the meeting, the group was provided the initial comprehensive list of factors for review. The group was divided into three workshops, each facilitated by a study team member. The factors on the comprehensive list were reviewed and discussed in the workshops. TAG members were asked their opinions on the validity of the initial list, the relative importance of each factor, the manner in which the factors should be organized, the possibility of measuring the factors, and the feasibility of implementing the factors.

The individual workshops proved to be very useful for generating detailed discussions of some of the potential mode/route factors on the comprehensive list. There was a common recognition that substantial interrelationships existed among many of the factors and that the list could be better organized to reflect the relationships. Several categories of factors generated the most interest. These included emergency response and environmental factors. Most of the TAG members were familiar and comfortable with factors relating to population, accident rates, and shipment time and duration as mode and route selection factors. Environmental and emergency response factors were recognized as important safety considerations by all TAG members, but there was disagreement on whether these were mode/route discriminators. Some TAG members were strongly in support of both factors, while others completely disagreed that they had any relationship to mode/route selection.

During the course of the workshops, a number of important issues surfaced that were related to this study. This was helpful to put the study into context. Some of the issues could be addressed, and the study approach was adjusted accordingly. Other issues could not be addressed because their resolution would go beyond the scope and resources of the project.

One issue was the context and timeframe for which this study was to apply. The specific concern raised was that the context for this study should be the commercial radioactive waste program and, therefore, the timeframe should be for the next 10 to 20 years. The argument was that almost all of the future shipments of high-level radioactive waste and spent nuclear fuel would be the movement of commercial reactor waste from utilities to a repository. Further, the only candidate location for such a repository at this time is Yucca Mountain, Nevada. Thus, the consideration of mode/route factors should be designed primarily to address the specific issues and the long planning horizon related to that program. Others disagreed that this study should be tailored to the commercial repository program, however important that will be in the future.

Another issue of concern was whether the project definition of public safety should include perceived risk. Almost everyone agreed on the importance of risk perception in public acceptance of radioactive material transportation. It was also agreed that perceived risk directly impacts some decisions about transporting these materials. The question was how to reconcile perception and reality in a study such as this. It was noted that addressing perceived risk is not something that can actually enhance safety in the same manner as addressing actual risk, such as incident-free exposure and accident risks. It was pointed out that perceived risks can actually be addressed by doing a better job in addressing the actual risk factors. Consequently, it was decided not to include perceived risk within the project definition of public safety.

Another issue addressed by the TAG was intermodal shipments. To scope the range of modal and intermodal options to be addressed by this study, the project team proposed to the TAG members that not all intermodal combinations need to be addressed in detail by this study because of the significant exposure resulting from intermodal transfer of the casks. Previous studies have shown that this exposure greatly increases the total exposure and overall risk of shipments. There was general acknowledgment that the intermodal transfer exposure is a very significant factor that tends to favor single mode transport. Some members, however, felt very strongly that intermodal combinations should be considered for at least two options. First, for the present transportation infrastructure, a highway link between rail and the potential commercial repository site in Nevada would be required. Second, because barge transport is being considered, a barge/rail route would be the most feasible option since cask size limitation for trucks would make barge/highway impractical. These recommendations were adopted in the study approach.

The issue of weighting radiological and non-radiological risk was also brought up by some TAG members. This has always been a major area of concern in conducting risk assessments for transporting radioactive materials. The issue is whether these components of risk should be given equal weight. Some argued strongly that non-radiological risk should not be included as a primary routing criteria with the same level of importance or weight as radiological risk because it does not address the risk from the nature of the cargo. If non-radiological risk is included on the same level as radiological, then the overall risk of transport is dominated by the non-radiological accident impacts, since non-radiological accidents occur far more frequently than accidents involving a radiological release. Thus, the risk analysis would always find that the mode/route combinations with the lowest general accident rate would be the safest route. Others argued that non-radiological impacts are, in fact, legitimate impacts from shipping radioactive materials and that it would be inappropriate to exclude them. This issue involves significant policy considerations and was not resolved as a part of this study. It was decided by the project team that non-radiological impacts should be included as a component of the project definition of public safety since it is traditionally included in risk assessment studies. Also, since it is not an objective of this study to assign weights to mode/route factors, this issue did not have to be resolved to complete the study.

4.1.3. Distinction Between Mode and Route Factors. As the evaluation process developed, only a few factors could be identified that affect mode selection exclusively. For most factors, it was difficult to separate mode from route considerations. Three factors were found to be mode-only selection factors: (1) mode accessibility, (2) cask availability, and (3) amount of material to be shipped. The first two factors are obvious practical constraints in mode selection. If barge or rail is not accessible from a given location, or if a truck cask is unavailable, mode selection will be dictated without considering routes. However, these are short-term considerations that can be overcome with time and money if there are sufficient reasons to use a given mode.

The amount of material to be shipped is the single most important factor that could affect the choice of mode exclusively, because of the substantial difference in payload between truck and rail casks. A rail cask (which is also used for barge transport) has from four to seven times the payload of a truck cask. This ratio may actually increase for future generations of casks (unless an overweight truck cask is developed). This differential has an obvious impact on the number of shipments required for a given amount of material. The number of shipments, in turn, has a direct impact on the overall safety of a shipping campaign.

The rest of the factors on the comprehensive list did not affect either mode or route exclusively. The factors had to be considered within the context of the mode and route combination (including intermodal). For example, when comparing the safety of highway and rail between common origin and destination points, more than one route will usually be possible by either mode (especially for longer shipments). In addition, intermodal combinations with different routing and interchange points are possible. The risk for one rail route may be lower than the risk of a highway route, yet the corresponding risk for another rail route may be higher. Thus, it cannot be concluded that one mode is safer than another without considering the specific route.

Except for amount of material, mode accessibility, and cask availability, all other factors are considered a homogenous group of mode/route selection factors, not mode or route factors separately. The distinction between the mode-only factors (primarily the amount of material) and all of the other mode/route factors will be addressed later in the report.

4.2. Development of Factor Hierarchy

Based on the findings of the initial screening of factors and the results of the TAG review process, a hierarchical matrix was developed with the goal of organizing the enumerated list of factors into different levels for each of the three public safety categories defined in Section 1.2. The rationale for this approach is presented below.

4.2.1. Hierarchical Approach to Mode and Route Factors. During the screening process, any initially identified factor that did not affect public safety was deleted. It became very difficult to eliminate many factors, no matter how inconsequential the factors seemed to be, however, because the applicability of each potential factor depends on the level of analysis to be conducted. For example, excessive curvature along a route cannot be categorically excluded as unrelated to safety. It depends on how detailed the shipper, carrier, or public official intends the routing analysis to be (e.g., local, regional, or national in scope).

To evaluate a route at the local level (e.g., comparing two mode/route alternatives over a distance of 40 miles), a shipper may want to include such microscopic factors as high-accident locations ("hot spots"), grades, or structures along the route of travel. On the other hand, if the shipment is cross-country for 1,500 miles, the level of analysis needs to be more general. The analyst would not, and probably could not, be able to account for the myriad of microscopic factors. Taken together, however, all three of the microscopic factors mentioned above are components of the infrastructure along the route, which, in turn, is a prime determinant of the accident rate. Thus, the accident rate represents a higher level factor that can be used for regional and national analyses to help select modes/routes. In this way, the accident rate implicitly accounts for all the individual infrastructure factors at the lower end of the hierarchy.

The hierarchical approach to selecting mode/route factors allows adjustment of the level of analysis to the shipment situation. Many of the microscopic factors that have been identified in the past are valid for very short distances. The details, however, become unmanageable for regional and national shipments. The hierarchy shows that the analysis can be simplified by using factors at the upper end of the hierarchy, since they are fewer and more feasible to measure, and data are more readily available for them. Furthermore, these higher level factors are legitimately representative of the lower level factors, as shown by the hierarchical relationships.

The three categories of impact from the definition of overall public safety (incident-free exposure, potential radiological accident exposure, and potential non-radiological accident impact) were considered separately in establishing the hierarchical factor matrix. Each factor from the comprehensive list was evaluated to identify which category or categories it affected and how it was related to other factors within that category. These relationships could be divided into two types: (1) factors that were subsets of other factors and (2) factors that could have a direct effect on another factor. An example of the first type would be people in hospitals as a subset of special populations, which is a subset of total population. An example of the second type would be road conditions that could affect the speed of the vehicle, which, in turn, would affect the overall shipment duration, which then affects the amount of incident-free exposure.

4.2.2. Hierarchy for Incident-Free Radiological Exposure. The comprehensive list of factors was carefully reviewed to determine which factors affect incident-free exposure during transportation. These factors were then evaluated for interrelationships. The major factors influencing normal dose from radioactive material transportation were the number of people potentially exposed and the amount of exposure time. The rest of the factors are lower-level, but nonetheless important, elements that contribute to these two major factors and are subsets of these two primary factors.

For people potentially exposed, the major dichotomy is the potential exposure of the general population versus the occupational population. These are treated as two separate mode/route factors because of their fundamentally different impacts (involuntary, short-term, and distant exposure versus voluntary, longer-term, and close proximity exposure).

General population exposure can be segmented into several major subfactors: residential, non-residential, and "special." *Residential* population represents Census population. Non-residential population can be broken down into *employment* population (which recognizes that time-of-day population varies considerably as people go from home to work and back), *tourists*, *people in other vehicles* along the right-of-way, and *people at stops* (see Table 5). An important related issue for this factor is the distance from the right-of-way to affected populations.

Occupational population exposure consists primarily of two subgroups: (1) on-board crew and nearby escorts and (2) support workers (such as handlers) at the shipment origin, destination, and transfer points, as well as inspectors and security staff. This would also include emergency response personnel at the scene of a non-radiological traffic accident involving a vehicle carrying radioactive material..

The other primary factor for incident-free exposure is time of exposure or ***shipment duration***. Many factors in the comprehensive list could affect shipment duration. These can be categorized into three major subfactors: (1) route length, (2) vehicle speed, and (3) stops enroute. *Route length* is

Table 5. Factor hierarchy for incident-free radiological exposure.

General Population

- Residential
- Non-Residential
  - People at work
  - Tourists
  - Pedestrians
  - Shared-facility users in other vehicles at stops
  - Shared-facility users on route
- Special Populations
  - Hospitals
  - Schools
  - Prisons
  - Events

Occupational Population

- On-board/nearby
  - Crew
  - Escorts
- Support
  - Handlers
  - Security
  - Inspectors
- Emergency
  - Responders to non-radiological incident

Amount of Material

- Number of shipments
- Packages per shipment
- Size of cask
  - Cask availability
  - Waste type/level of radioactivity
  - Cask size limitation

Shipment Duration

- Length of route
  - Origin/destination distance
- Vehicle speed
  - Normal operation
    - functional classification
    - posted speed
    - operating speed
    - traffic density
    - traffic mix
    - maintenance
    - time of day
    - work rules
    - movement control
    - enforcement
    - time of day restrictions
  - Delays
    - communication
    - seasonal road conditions
    - hot spots
    - incident/accident rate
    - available detours
    - right-of-way maintenance
    - weather/climate
    - visibility/lighting conditions
- Stops
  - Number of stops
    - interchanges
    - classifications
    - handlings
    - inspections
    - equipment changes
    - pick-up/drop-off route
    - union vs. non-union rules
    - delays in/out of origin/destination
    - priority passing
    - locks and dams
    - sabotage
  - Stop times

simply the distance between the origin and destination. *Vehicle speed* can be influenced by many factors, including both normal operations and delay conditions. Some of these include the posted speed limit, type of highway, traffic density, and time of day. *Stops enroute* include the number of stops and stop times. These can be affected by the number of interchanges, inspections, classifications, breakbulk operations, equipment changes, union rules, fuel stops, and other factors.

It should be noted that several members of the TAG group argued that there is an incident-free radiological exposure to the environment. This potential impact, however, has never been measured and others in the TAG believed that such an impact, if it exists, is inconsequential. It is not included as a factor in this study.

The ***amount of material*** is not a factor that affects incident-free radiological exposure in terms of mode/route selection on a shipment-by-shipment basis. Regulatory requirements limit the amount of surface radiation regardless of the size of package or the mode. The amount of material, however, can become a factor for mode selection if it necessitates multiple shipments. If the amount of material to be shipped exceeds the capacity of a single truck cask, then the shipper must choose between several modes with different container capacities. This would affect the number of shipments and, ultimately, the total incident-free exposure from an entire shipping campaign.

In summary, four primary factors were identified that affect mode/route choices because of their influence on incident-free exposure. These are (1) general population exposure, (2) occupational exposure, (3) shipment duration, and (4) amount of material. Each of these is comprised of a number of components or subfactors, which are arranged in a hierarchy and presented in Table 5.

4.2.3. Hierarchy for Radiological Accident Exposure. Using the same procedure as for incident-free radiological exposure, the comprehensive list was culled for factors that could conceivably affect radiological accident exposure. This category of public safety is more complex than the incident-free category, however. First, two major subcategories of factors influence potential accidents that are severe enough to cause a release of material: (1) accident likelihood (probability) and (2) accident consequences. Each of these is composed of a number of other factors. Second, two major types of impact could result from a release: (1) impact on people and (2) impact on the environment. Impact on property is a third type of impact from a release. Finally, emergency response capability must be considered, since it can have a significant effect on the magnitude of consequences following an accidental release.

Accident Likelihood. All factors that could affect the likelihood of an accident during transportation were identified. A number of these fall under the category of *infrastructure*. These include the classification of the right-of-way, grade and elevation, geometry and curvature, structures and clearances along the right-of-way, bottlenecks, and even maintenance practices of the authority responsible for the quality of the right-of-way. Two other subfactors that could contribute to accident likelihood are the operating practices of carriers and quality control. Although these would not normally be considered routing-related factors, they could have an influence on accident potential because they address the issue of quality of carrier. *Carrier operating practices,* although subject to minimum regulatory rules (such as driver service hours), can be substantially different from one mode to another and from one carrier to another. *Quality control* can affect accident likelihood and includes internal company procedures and degree of oversight to ensure quality performance. Quality control factors include training, maintenance policy, hiring policy, and drug and alcohol enforcement.

Each of these three factors—(1) infrastructure, (2) operating practices, and (3) quality control—is a major contributor to the accident likelihood along a given mode/route combination. Thus, ***accident rate*** is considered a primary factor, as is ***length of trip,*** since it is traditionally applied to the number of accidents to determine the accident rate (see Table 6).

Accident Consequences. As intimated above, three major factors relate to this category: (1) general population, (2) occupational population, and (3) environment. Obviously, the population within the proximity of an accidental release of radioactive materials is the major component of accident consequences. The subfactors of ***general population exposure*** and ***occupational exposure*** were

Table 6. Factor hierarchy for radiological accident exposure.

Accident Rate	Length of Trip	Sensitive Environment
Infrastructure	Distance	Water supply
Functional classification	Speed	Reservoirs
Opposing traffic separation	Weather conditions	Sensitive areas
Grade	Route restrictions	Wetlands
Curvature	Number of stops	Refuges
Crossings		Sacred tribal grounds
Hot spots	**General Population**	
Posted speed	Residential	**Emergency Response**
Clearance	Non-residential	Preparedness
Maintenance	People at work	Training
Structural impediments	Tourists	Equipment
Wayside detectors	Pedestrians	Response
Operating procedures	Shared-facility users in other vehicles at stops	Proximity
Time of day		Accessibility
Work rules	Shared-facility users in other vehicles on route	Capability
Quality control		Communication
Training	Special populations	Time to medical care
Movement control	Hospitals	Evacuation
Hiring practices	Schools	
Enforcement	Prisons	**Amount of Material**
Vehicle maintenance/inspection	Events	Number of shipments
Licensing		Size of cask
Substance abuse enforcement	**Occupational Population**	Cask availability
Sabotage and vandalism	On-board/nearby	Waste type/level of radioactivity
Human error	Crew	Cask size limitations
Weather/climate	Escorts	
Seasonal road conditions	Support	
Visibility/lighting conditions	Handlers	
	Security	
	Inspectors	
	Responders	
	Fire, police, etc.	

discussed in Section 4.2.2. A third major factor under accident consequences is ***sensitive environments,*** because of the growing concern about long-term public health effects of contamination of sensitive environmental areas as a result of transportation spills. The definition of what is "sensitive" and what can reasonably be avoided during long-distance shipments, however, make this factor more difficult to measure. The two principal environmental subfactors initially identified are water supply areas (such as reservoirs) and sensitive areas (such as wetlands, refuges, and sacred tribal grounds).

A fourth component of accident consequences was identified separately as a primary factor. The ***emergency response*** along potential modes and routes of travel can be significant in limiting the consequences of an accident. Several key subfactors determine the level of efficiency of emergency response. Emergency preparedness (training, plans, and equipment) and actual emergency response operations (capability, proximity, and accessibility) are the key factors.

The last major consequence of a radiological accident is the ***amount of material*** to be shipped. As discussed in the last section, the amount of material is important because it could affect the number of shipments required. Also, the amount of material (size of cask) could affect the size of a potential release during an accident.

In summary, seven primary factors affect mode/route choices because of their influence on radiological accident exposure: (1) accident rate, (2) trip length (both reflecting accident likelihood), (3) general population exposure, (4) occupational exposure, (5) sensitive environments, (6) emergency response (all of which reflect accident consequences), and (7) amount of material (which is included because it could affect the number of shipments required). Table 6 lists the primary factors for radiological accident exposure, arranging associated subfactors in a hierarchy.

4.2.4. Hierarchy for Non-Radiological Accident Impact. Determining the non-radiological accident impact was handled differently than the first two categories, because the impacts are related to injuries or deaths as a result of vehicular accidents and are unrelated to the radioactive nature of the cargo. It is included as a public safety impact because shipping spent nuclear fuel may necessitate additional trips on the transportation infrastructure, introducing an additional non-radiological traffic impact that otherwise would not exist. This would certainly be true for highway, dedicated train, and probably barge shipments, although probably not for regular train shipments.

The two major factors in this category are (1) ***accident rate*** and (2) ***trip length***. Accident rate is represented by a number of other lower-level factors, as discussed in Section 4.2.3. The major subfactors include infrastructure, carrier operating procedures, and quality control. ***Amount of material*** is also included as a primary factor because of its effect on the number of shipments required.

In summary, three primary factors were identified that affect the mode/route choice because of their influence on non-radiological accident impacts: (1) accident rate, (2) length of trip, and (3) amount of material. Table 7 lists these primary factors for non-radiological accident impact, arranging associated subfactors in a hierarchy.

Table 7. Factor hierarchy for non-radiological accident impact.

Accident Rate		**Amount of Material**
Infrastructure	Quality control	Number of shipments
Functional classification	Training	
Opposing traffic separation	Movement control	
Grade	Hiring practices	
Curvature	Enforcement	
Crossings	Vehicle maintenance/inspection	
Hot spots	Licensing	
Posted speed	Substance abuse enforcement	
Route length	Sabotage and vandalism	
Clearance	Human error	
Traffic density	Weather/climate	
Maintenance	Seasonal road conditions	
Structural impediments	Visibility/lighting conditions	
Wayside detectors		
Operating procedures	**Length of Trip**	
Time of day		
Work rules	Distance	
	Speed	
	Weather conditions	
	Route restrictions	
	Number of stops	

4.3. Identification of Primary Factors

Table 8 presents the list of primary mode/route factors identified for the three categories of impacts on overall public safety. These factors are primary because they are at the top of the factor hierarchy previously discussed and are representative of a number of subfactors positioned lower in the hierarchy.

The eight primary factors are listed in the first column of Table 8. The applicability of these factors to each of the three components of public safety are given in the next three columns. For example, "general population exposed" includes all of the population along the route of travel for incident-free exposure and the population within an affected area for radiological accident exposure. Population exposed is not considered a primary factor related to non-radiological accident impact. The other primary factors are treated in a similar manner.

It is apparent from Table 8 that, although eight primary factors are identified, they do not affect all components of public safety. Some of these factors affect two components of public safety, while others affect only one component. To be identified as a primary factor, at least one component of public safety must be significantly affected.

Further, each of the primary factors may be measured differently from one component of public safety to another. An example is measuring accident rate. For radiological accident exposure, the likelihood of a release-causing accident would be an appropriate measure, while for non-radiological accident impacts, the likelihood of an injury or fatality-related traffic accident (without considering release) would be a more relevant measure.

Table 8. Recommended primary mode and route factors.

Primary Factor	Incident-Free Radiological Exposure	Radiological Accident Exposure	Non-Radiological Accident Impact
General Population Exposed	People along route	People in area affected by accident	Not a primary factor
Occupational Population Exposed	People moving and handling material	People moving material and responders	Not a primary factor
Environment Exposed	Not a factor	Environment in area affected by accident	Not a factor
Shipment Duration	Length of time material is transported	Not a factor	Not a primary factor
Accident Rate	Not a factor	Likelihood of accident releasing material	Likelihood of traffic accident with injury/fatality
Trip Length	Not a primary factor	Accident likelihood	Accident likelihood
Emergency Response	Not a factor	Length of time for trained responders	Not a primary factor
Amount of Material*	Number of shipments required	Number of shipments required	Number of shipments required

* Amount of material is the only primary factor identified that could dictate mode by itself. This is because of its impact on the number of shipments required, given the cask payloads of highway vs. rail transport modes.

Finally, the amount of material is listed as a primary factor because of its effect on the number of shipments required, which is perhaps the key factor for mode selection. The number of shipments required is determined by the quantity of material to be shipped and the cask payload. A rail cask payload can be four to seven times that of a legal weight truck cask. Thus, four to seven times as many truck shipments are required to move the same amount of material as moved by rail or barge. This difference must be taken into account when comparing the relative impact on public safety among the three modes.

It should be noted that it also is possible to include more than one cask per shipment for rail and barge shipments. Thus, it is theoretically possible to move ten, twenty, or more casks (if they were available) in a single rail or barge shipment, if there is enough material to be moved at one time. This would necessitate an even greater multiple of truck shipments to move the equivalent amount of material. Shipments by rail or barge from different locations could even be consolidated to obtain multiple casks per shipment.

To facilitate the comparison of mode and route factors on a shipment-by-shipment basis without the complications of considering the effects of multiple casks per shipment, this study addresses mode and route factors only on a single cask per shipment basis. When the specific circumstances of a particular shipping campaign are known, the effect of multiple casks per shipment by rail or barge should be the subject of systems analyses and trade-off studies. Based on the results of such studies, the shipper should then consider the effect of multiple casks per shipment in the selection of the mode and route.

4.4 Representative Units of Measure for the Primary Factors

The primary factors listed in Table 8 are presented on a "generic" level. As stated earlier, even the best mode/route factor is really of little use in selecting mode/routes if it cannot be measured. To conduct an actual mode/route comparative analysis, it is necessary to identify the precise item that is to be compared. The project team has identified the most representative unit of measure for each primary factor. These are presented in Table 9. These units of measure will serve as the basis of the case study analysis presented later in this report.

Table 9. Representative units of measure for primary mode and route factors.

Primary Factor	Representative Units of Measure
General Population Exposed	Census population within designated bandwidth along route in miles/kilometers
Occupational Population Exposed	Number of drivers and other transport workers involved during shipment
Environment Exposed	Number of environmentally sensitive areas within designated bandwidth along route
Shipment Duration	Transit time in hours (including stops)
Accident Rate	Number of fatalities based upon fatal accident rate and route length (fatal accident rate)
Trip Length	Trip distance in miles
Emergency Response	Average time to respond for qualified units in minutes/hours
Amount of Material	Number of shipments required based upon cask payload

5.0. Identification of Primary Mode and Route Factors by Modeling Risk of Transporting Radioactive Materials

Chapters 3 and 4 describe the development of a comprehensive list of mode/route factors that represent diverse interests identified through an exhaustive review of work and literature in the field. A qualitative evaluation of these factors resulted in the development of a factor hierarchy for each component of public safety from which a set of primary mode/route factors was identified. This chapter presents a modeling approach to identifying primary mode and route factors. Modeling the relationship between various factors that contribute to nuclear transportation risk serves two purposes: (1) it allows a comparison of factors developed in this way with the factors developed using the hierarchical approach described in Chapters 3 and 4, and (2) it helps establish the nature and type of relationship between each primary factor and the three components of risk that make up the project definition of public safety.

5.1. Elements of Risk

As noted previously, risk is composed of incident-free radiological, accident radiological, and accidental non-radiological impact to different population groups. These groups can be categorized as follows:

- **Off-link population**—people residing, working, or otherwise congregating in areas within the zone of radiation impact from the route of spent nuclear fuel shipment
- **On-link population**—people in other vehicles along the route
- **Crew**—transport crew, on-board security and emergency response personnel, and inspectors (within the immediate vicinity of the cask)
- **Population at stops**—other transportation workers, including emergency responders during an accident and people near the stops (away from the immediate vicinity of the cask)
- **Handling personnel**—workers at an intermodal transfer facility.

The relationships developed in the following sections include determining incident-free, radiological, and non-radiological accident risks. The quantitative measure of radiological exposure is the combined dose to all persons exposed as measured in person-rems. Non-radiological accident exposure is measured in expected fatalities. The relationship between these measures has been expressed in the past by converting aggregate radiation exposure into expected fatalities. For example, in the Monitored Retrievable Storage Review Commission report[20], an equivalency of one latent cancer fatality per 2,500 person-rem was used. Each of the above components of the overall risk are analyzed with a view to grouping different parameters.

5.2. Model Development

The models described below are derived from basic physics with the following simplifying assumptions:

- The applicable models are mode-specific; separate coefficient values are generated for each mode, resulting in a unique model for each respective mode.
- The width of incident-free radiation effect zones is a constant within each mode.
- An individual shipment contains a single cask; multiple cask shipments are *not* considered.
- Only risks to handlers at intermodal transfer facilities are considered.

Detailed derivations of the model equations and nomenclature presented in this section appear in Appendix F.

5.2.1 Incident-Free Exposure (IFE) Model. The total incident-free radiation exposure from a single shipment on a specified mode from any origin to destination consists of the sum of the component risks to each population category:

$$R_{IFE} = R_1 + R_2 + R_3 + R_4 + R_5 \tag{1}$$

where:

R_{IFE} = total risk (in person-rem) due to incident-free exposure
R_1 = risk to off-link population
R_2 = risk to on-link population
R_3 = risk to crew
R_4 = risk to population at stops
R_5 = risk to handlers

Model formulations for each of the incident-free component risks are as follows.

Off-Link Population Exposure. Off-link population exposure is a function of the duration of exposure to each person along the route and is expressed by

$$R_1 = a_1 \times \left[\begin{matrix}\text{number of persons} \\ \text{exposed over the route}\end{matrix} \times \begin{matrix}\text{average duration of} \\ \text{exposure of each individual}\end{matrix}\right] \tag{2}$$

i.e.:

$$R_1 = a_1\, p\, t_L \tag{3}$$

where:

a_1 = the coefficient for off-link population exposure
p = mean population density over the route within the exposure range of significant radiation
t_L = overall shipment duration from origin to destination, excluding stop times.

On-Link Population Exposure. The on-link population exposure value, R_2, is also a function of the duration of exposure to each individual and is represented by

$$R_2 = a_2 \times \left[\begin{matrix}\text{number of people}\\ \text{exposed on route}\end{matrix} \times \begin{matrix}\text{average duration of}\\ \text{exposure of each individual}\end{matrix}\right] \tag{4}$$

with:

$$\begin{matrix}\text{number of}\\ \text{people}\\ \text{exposed}\end{matrix} = \begin{matrix}\text{number of on-link}\\ \text{vehicles passing a}\\ \text{point per hour}\end{matrix} \times \begin{matrix}\text{average number}\\ \text{of people aboard}\\ \text{on-link vehicle}\end{matrix} \tag{5}$$

$$\begin{matrix}\text{average duration}\\ \text{of exposure}\end{matrix} = \frac{\begin{matrix}\text{average distance on the passing or same}\\ \text{lane with significant radiation effects}\end{matrix}}{\begin{matrix}\text{mean relative velocity between}\\ \text{cask vehicle and other vehicles}\end{matrix}} \tag{6}$$

The above equations reduce to

$$R_2 = a_2\ T\ t_L^2/L \tag{7}$$

where:

a_2 = coefficient for on-link exposure
T = on-link traffic density (vehicles/hr)
L = route length
t_L = overall shipment duration from origin to destination, excluding stop times.

Crew Exposure. Crew exposure is a function of the duration over which each crew member is exposed to radiation from the cask and is represented by

$$R_3 = a_3 \times \left[\begin{matrix}\text{number of crew}\\ \text{and inspectors}\end{matrix} \times \begin{matrix}\text{average duration of}\\ \text{exposure of each individual}\end{matrix}\right] \tag{8}$$

Crew exposure is then given by

$$R_3 = a_3\ N_{crew}\ t_L \tag{9}$$

where:

a_3 = coefficient for crew exposure
N_{crew} = average number of persons on-board the vehicle.
t_L = overall shipment duration from origin to destination, excluding stop times.

The value of a_3 will vary by mode because the distance between the crew and the cask will be different.

Exposure to Population at Stops. The total exposure at various stops can be represented by

$$R_4 = a_4 \times \left[\frac{\text{number of stops}}{\text{over route length}} \times \frac{\text{avg. number of persons}}{\text{exposed per stop}} \times \frac{\text{avg. duration}}{\text{of exposure}} \right] \qquad (10)$$

It is assumed that the number of stops is directly proportional to the distance traveled,* and that at each stop only a certain number of persons are exposed (based on an average population at stops and a constant radiation affected area by mode). Hence

$$R_4 = a_4 L \qquad (11)$$

where:

a_4 =coefficient for stop exposure
L =route length.

Handling Personnel Exposure Risk. Handling risk is assumed to arise only in the case of intermodal transfers when casks have to be handled by transportation personnel. Both the number of handlers and the average duration of handling are assumed to be constant. Hence, the risk itself is considered as a constant, irrespective of the distance of transportation. This is represented by

$$R_5 = a_5 H_1 \qquad (12)$$

where:

a_5 = coefficient for handling exposure
H_1 = Boolean variable (1 for intermodal shipments; 0 otherwise).

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* The assumption of number of stops being proportional to distance may not apply for very short distances.

Overall Incident-Free Risk Expression. By summarizing the component risks, overall incident-free exposure can be specified as

$$R_{IFE} = a_1 \, p \, t_L + a_2 \, T \, \frac{t_L^2}{L} + a_3 \, N_{crew} \, t_L + a_4 \, L + a_5 \, H_1 \quad (13)$$

The terms are measured in different units and are, therefore, not dimensionally consistent. The product of the coefficients and their respective parameter groups, however, have units of radiation dosage expressed in person-rems.

The simplified equation for overall incident-free risk (equation 13 above) contains the same factors previously identified in Table 8 as primary factors affecting incident-free exposure. These factors include general population (p and T), occupational population (N_{crew} and H_1), and shipment duration (t_L). Trip length (L) is not listed in Table 8 as a primary factor, but it is obviously an important component of shipment duration. Furthermore, the equation mathematically shows the type of relationship that each variable (factor) has with overall incident-free risk.

5.2.2 Radiological Accident Exposure (ACE) Model. The radiation exposure from transportation accidents resulting in cask failures and radioactive material releases can be represented as follows

$$R_{ACE} = \begin{matrix}\text{probability of an}\\ \text{accident release}\end{matrix} \times \begin{matrix}\text{consequence of release}\\ \text{(in person-rem)}\end{matrix} \quad (14)$$

Using the above equation and assuming that the principal radiation exposure pathway to the population is by dispersing radioactive material (radionuclides), risk can be expressed as

$$R_{ACE} = b \, p^* \, S_A L \quad (15)$$

where:

b = coefficient for radiological accident exposure

p* = mean density of population potentially exposed to the effects of the dispersing radioactive cloud (including occupational population)

S_A = mean traffic accident rate over the entire route (probability of an accident per unit distance in a given shipment)

L = route length

In deriving equation 15, the probability of release of radioactive material given that an accident occurs is assumed to be a constant within each mode.

Equation 15 contains factors that were presented in Table 8 as primary factors affecting radiological accident risk. These include the accident rate (S_A), the trip (route) length (L), and the population at risk (p). Again, the type of relationship between these factors and the manner in which each contributes to overall radiological accident risk is illustrated by the model. Equation 15 does not include two factors identified in Table 8 as primary: environment and emergency response.

5.2.3 Non-Radiological Accident Exposure (NAE) Model. The risk to the population from vehicle accidents that do not have radiological consequences is represented as

$$R_{NAE} = \begin{array}{c}\text{probability of a}\\ \text{serious accident}\end{array} \times \text{length of route} \tag{16}$$

Using the above equation and assuming that the measure of non-radiological accident exposure is fatalities, the risk can be expressed as

$$R_{NAE} = S_{AF}L \tag{17}$$

where:

S_{AF} = mean traffic fatal accident rate over the entire route (probability of an accident resulting in at least one fatality per unit distance for a given shipment)

L = route length.

The resulting risk is expressed as expected number of fatalities.

Equation 16 above relates directly to Table 8, which identified accident rate and trip length as primary factors contributing to non-radiological accident risk.

5.3 Relationship of Risk Modeling to Mode/Route Factors

The relationships described in this chapter present a method for evaluating the risk of shipping spent nuclear fuel for different modes through association with key mode and route factors. Their development was based on the physical relationships between key factors that affect component risks. The values of model coefficients in the formulations can be estimated using any method that consistently derives factor and risk values between modes and routes and utilizes this information within accepted statistical estimation techniques.

Table 10 provides a matrix that summarizes the relationship between key mode/route factors identified through development of the risk models presented in this chapter. As noted, incident-free risk is derived from consideration of general population, occupational population, trip length, and shipment duration (excluding stop times). This comes from the need to consider these factors in various relationships that describe component risks related to off-link, on-link, crew, stop, and handling exposures. Radiological accident risk is directly related to general population, accident rate, and trip length as primary factors. Non-radiological accident risk is derived from consideration of accident rate and trip length.

Table 10. Relationship of risk modeling to primary mode/route factors.

	General Population	Occupational Population	Accident Rate	Trip Length	Shipment Duration
Incident-Free Risk	x	x		x	x
Off-Link	x				x
On-Link	x			x	x
Crew		x			x
Stop	x	x		x	
Handling		x			
Radiological Accident Risk	x	x	x	x	
Non-Radiological Accident Risk			x	x	

Collectively, the fundamental relationships, as established, share five of the eight primary factors identified in Chapter 4. Amount of material, emergency response, and environmentally sensitive areas are the remaining factors potentially linked to public safety that are not explicitly represented in the model formulations. These effects can be incorporated into the process, however, using the following approaches.

Amount of material is implicitly represented in the prescribed approach as a single shipment of a single cask. Assuming linearity and using a post-processing activity once the relationship between primary factors and safety is established on a per shipment basis, this factor can be included in the risk models. The relative payload capacity becomes the determinant of the number of shipments required for comparative analysis.

Proximity to effective emergency response potentially lowers radiological accident risk by reducing the number of people exposed and duration of exposure. This is not considered in the models, as presented. Knowledge of the location of qualified responders with respect to the route being evaluated, however, can provide a measure of this effect.

Environmentally sensitive areas are exposed to radiation similar to population groups. Model development could be extended to environmental areas by measuring the size and character of the affected area and predicting the associated consequences. This development is dependent on obtaining information about these areas and subsequently establishing the fundamental relationships that would apply.

Each of these three factors will be addresed again later in the report.

6.0. Case Study and Statistical Analysis of Factors

The case study was designed to accomplish three objectives: (1) demonstrate the feasibility of measuring and estimating the previously identified mode/route factors in a complex analysis environment, (2) statistically evaluate the variability of mode/route factors across various modes and routes, and (3) evaluate in more detail the specific relationship of the mode/route factors with public safety. To address these considerations, transportation risk management models were used to measure primary factor values and to calculate risks of transporting a single shipment (truck or rail/barge cask) between selected origins and destinations by various modes. Model inputs and outputs also supported the estimation of radiological risk equations, from which a sensitivity analysis of the effects of the primary factors on risk estimates was performed.

6.1 Development of Analysis Framework

The analytical environment for achieving the case study objectives required selecting sample modes and routes thought to be representative of spent nuclear fuel shipments and subsequently deriving and analyzing factor and risk values for each case. An integrated approach combining two previously developed transportation risk assessment tools was used to develop factor inputs and calculate risk measures across several mode and route combinations for each origin-destination (O/D) pair. Model coefficients using the data for each case were then estimated.

6.1.1. Selection of Sample Routes. To develop the case study, a series of possible shipment O/Ds was selected that represents historical or anticipated campaigns. The selection criteria included actual spent fuel shipment origins and likely destinations with access to all three modes and intermodal shipments; differing route lengths, infrastructures, and populations; and travel in different parts of the country. An effort was made to include routes that passed through large urban areas, as well as routes that were predominantly rural. The shorter-distance shipments were felt to be representative of intra/inter-utility shipments, while the longer-distance shipments could be considered typical for transport to either monitored retrievable storage or long-term storage facilities.

The following modes were considered in the case study: (1) highway, (2) manifest (scheduled) rail, (3) dedicated rail, (4) waterway, and (5) intermodal. Manifest and dedicated rail were considered separate modes because the characteristics of the train configurations and their operations are significantly different. All intermodal shipments were grouped together because they involved waterway/rail combinations where the waterway movement and intermodal handling activities were common characteristics.

For each O/D pair, analyses were separated by mode; within each mode, analyses were performed for several routes. The criteria used to select prospective routes included identifying both economical routes (those that minimize travel time) and routes that offer a significant reduction in exposure by avoiding heavily populated areas. By using this approach, a wide range of candidate routes were represented, and the characteristics of direct and more circuitous routings could be examined. Routes were also selected on the basis of combined consideration of travel time and population exposure, as well as population exposure and accident likelihood. Additionally, minimizing the number of interchanges was considered in rail route selection.

The HazTrans routing and risk management model was used in the selection of candidate routes on the basis of multiple criteria. Appendix D contains additional information on HazTrans. An optimization routine within HazTrans permits selection of preferred routes on the basis of minimizing trip distance, travel time, population exposure, accident likelihood, or weighted combinations involving two or more of these criteria. By applying this process, up to three routes were identified for each mode and O/D. In some cases, where different criteria resulted in the selection of the same route, fewer routes were analyzed. Each identified route was carefully reviewed for transport feasibility prior to its inclusion in the analysis. Table 11 summarizes the 65 unique mode and route combinations generated from this process.

Table 11. Summary of routes used for case study.

Length	Mode	Origin/ Destination Pairs	Total Number of Routes
Short	Water	2	2
Short	Rail	2	4
Short	Highway	2	6
Moderate	Water	2	2
Moderate	Water/Rail	2	4
Moderate	Rail	4	14
Moderate	Highway	4	11
Long	Water/Rail	2	4
Long	Rail	2	12
Long	Highway	2	6
	TOTAL		65

6.1.2. Data Collection. Each sample route required collecting primary factor values and calculating associated risks. This necessitated the development of a hybrid analysis environment using two assessment models; HazTrans was used to derive the primary factor values and non-radiological accident risks, while Radtran 4 was used to calculate the radiological risks based on HazTrans input. Appendix E contains additional information on Radtran 4.

6.1.3. Development of Primary Factor Values. The primary factors for which quantifiable data were readily available included amount of material, emergency response, general population, occupational population, accident rate, trip length, and shipment duration. The development of quantitative measures for environmentally sensitive areas was not practicable given the time and resource constraints on this project. Appendix G contains a detailed description of the measures and assumptions used to develop primary factor values.

The HazTrans system was also used to measure several primary factor values. HazTrans contains an intelligent mapping system with truck, rail, barge, and intermodal analysis capability. These transportation networks are defined using geographic information system (GIS) coordinates, permitting direct association of the transportation system with the surrounding population and location of emergency response capability. Furthermore, characteristics of each individual route segment are stored within HazTrans and can be extracted to derive trip lengths, travel times, and accident rates. Since the version of HazTrans available to this project maintains only the principal highway, rail, and waterway networks, new links were defined to connect the transportation network to shipment origination or receiving points, as necessary.

6.1.4. Development of Risk Values Using Radtran 4. Radtran 4 is a risk assessment tool developed by DOE to calculate comprehensive radiological consequences from route-specific input. It was used in the case study to evaluate the radiological consequences of incident-free transportation, as well as the radiological risks from vehicular accidents during transportation. Radtran 4 contains mathematical models of radiation exposure in different transportation environments for several different radioactive materials. In this case study, default parametric values for spent nuclear fuel were used, as were standard cask sizes for each mode.

The five components of incident-free exposure include (1) crew risk, (2) handler risk (for intermodal only), (3) off-link (or surrounding) population risk, (4) on-link (or shared-facility user risk), and (5) stop risk (people exposed during stops). The four components of radiological accident risk include (1) groundshine (from external exposure to deposited particles), (2) inhalation (from breathing in particles), (3) resuspension (from inhalation of particles deposited and then resuspended), and (4) cloudshine (from external exposure to passing cloud). All risks are calculated in terms of person-rems.

Radtran 4 requires input data beyond mode- and route-specific parameters for the model to perform its function. These inputs were defined to maximize consistency in treating various modes and routes within the Radtran 4 analytical framework and were subsequently verified in discussions with selected shippers and carriers. Appendix G contains a detailed description of the input and assumptions used to perform these analyses using Radtran 4.

An important assumption in Radtran 4 is that, in handling and transporting spent fuel, workers and members of the public are expected to receive as much as, but not more than, the maximum radiological doses specified in Nuclear Regulatory Commission (NRC) and Environmental Protection Agency (EPA) regulations. The principal safety and environmental regulations applicable to spent nuclear fuel management are those of the NRC and the EPA. In practice, the expected doses could be less than the regulatory limits, because the system is designed to ensure a margin of safety. Doses are required to be kept as low as reasonably achievable.

To perform the analyses, the Radtran 4 route-specific option was used, which allows the analyst to include segment-specific information about length, vehicle speed, population density, traffic density, accident rate, and land use for every segment along the specified route. A special interface protocol between HazTrans and Radtran 4 was developed for this study to accommodate the transfer of route-specific data from HazTrans into Radtran 4 input formats.

Shipments were assumed in this study to move by exclusive-use vehicles (e.g., trailer, railcar, barge) requiring no storage during transit. This assumption eliminates the calculated risks to passengers (exclusive of crew and escorts) and storage personnel. Also, because ingestion risk calculations have been disabled within the current version of Radtran 4, the associated risk could not be obtained.

Since Radtran 4 does not model non-radiological transport risks, this measure was derived outside of the Radtran 4 methodology using HazTrans and national accident statistics. Non-radiological risk was measured as expected fatalities resulting from the force of a vehicular accident. National statistics have been compiled for each mode from which fatal accident rates can be derived that are relevant for this study. The derivations are explained in Appendix G.

6.2 Feasibility and Variability of Primary Mode/ Route Factors and Risk Values

This section describes how the feasibility of measuring and estimating the primary mode/route factors in a complex analysis environment was assessed. It is based on analyzing the sample database representing 65 mode/route combinations. Tables 12 through 15 display the results of statistical analyses performed on the sample to assess measurability and variability. These tables are addressed in detail in the following subsections.

6.2.1 Measurability and Variation in Primary Factor Values. This segment of the case study analysis focused on the measurability of primary factors and the extent to which their values may vary by mode and route for a given origin and destination. If the variation is not significant, then the primary factor cannot be a discerning factor in determining preferred shipment alternatives. Table 12 presents statistics associated with the values of each primary factor, organized by O/D. A grouped average of all O/D pairs is presented on the far right column of the table.

In reviewing Table 12 (and subsequent tables), it should be noted that "number of crew" is synonymous with *occupational population*. In addition, *shipment duration* has been reported as "average speed" for ease of presentation.

As noted by the variation and range, the values of primary factors fluctuate considerably across the case study sample for a given origin and destination. To illustrate from Table 12, the mean of population density for O/D Pair #1 was 73.27 persons per square kilometer. The lowest population density for potential mode/route combinations between this O/D pair was only 33.29 percent of the mean, or 24.39 persons per square kilometer. The highest population density was 162.42 percent of the mean, or 119.01 persons per square kilometer. This shows the substantial variation in population density between O/D Pair #1, depending upon the mode/route combination selected. It is evident from these results that primary factor values can be expected to change considerably by mode and route for different shipment lengths, shipment types, and locations in the

Table 12. Variation of primary factor values by O/D.

Factor	Origin / Destination Pair 1	Pair 2	Pair 3	Pair 4	Pair 5	Pair 6	Pair 7	Pair 8	All Pairs*
Length (km)									
mean	194.34	305.75	645.43	1117.30	955.82	2037.53	2264.26	4295.99	1477.05
min (% of mean)	88.19	62.42	86.64	72.16	82.54	72.56	86.27	85.74	79.57
max.(% of mean)	116.84	127.89	117.61	142.22	132.16	123.81	112.91	128.66	125.26
Population Density (per/km^2)									
mean	73.27	149.05	218.31	81.28	49.53	70.66	78.62	60.45	97.65
min (% of mean)	33.29	0.32	24.44	34.18	13.72	14.20	45.26	16.32	22.72
max.(% of mean)	162.42	262.96	164.08	198.68	204.38	241.33	180.07	176.32	198.78
No. of Crew									
mean	3.83	3.83	4.20	3.75	4.37	4.02	4.15	3.67	3.98
min (% of mean)	52.17	52.17	47.62	53.33	45.74	49.75	48.23	54.49	50.44
max.(% of mean)	260.87	260.87	238.10	266.67	223.00	212.22	228.30	203.04	236.63
Avg Speed (km/hr) (includes stop times)									
mean	21.85	21.79	19.78	21.08	18.92	20.88	18.83	19.33	20.31
min (% of mean)	11.38	13.62	17.79	28.02	29.05	40.24	36.03	37.58	26.71
max.(% of mean)	179.42	178.98	200.84	188.34	212.58	190.64	214.90	209.64	196.92
Accident Rate (acc/veh-km for highway and waterway; acc/car-km for rail)									
mean	3.16E-06	7.68E-07	2.03E-06	1.69E-06	1.93E-06	9.46E-07	1.58E-06	1.12E-06	1.65E-06
min (% of mean)	21.04	40.44	18.36	21.98	19.38	39.40	23.54	33.28	27.18
max.(% of mean)	302.65	149.12	323.74	447.95	461.56	248.39	482.46	425.63	355.19
Average Emergency Response Distance (km)									
mean	882.46	330.87	331.89	557.58	387.64	256.36	667.67	413.19	478.46
min (% of mean)	96.40	96.58	87.80	79.68	96.17	77.48	77.43	91.74	87.91
max.(% of mean)	101.88	108.76	106.34	108.83	101.23	125.04	115.58	103.72	108.92
No. of Cases:	6	6	5	8	9	9	11	11	8

* The statistics in this column were derived by treating each pair as a single observation. The mean, min., and max. values represent averages of the statistics presented in the first eight columns of this table.

* Where manifest and dedicated route values are identical only one was used in the calculation of the mean.

United States. It underscores the need to evaluate and identify those mode and route factors that significantly impact public safety.

6.2.2 Measurability and Variation in Risk Values. Tables 13 through 15 present summary case study values for incident-free, radiological accident, and non-radiological accident risks, respectively. Collectively, the information contained in these tables demonstrates that relevant data on primary factor values collected by mode and route can be successfully applied to a risk assessment methodology, resulting in a quantification of overall impacts to safety. The results also substantiate that risk values can be expected to vary considerably by mode, route, and O/D.

The tables also lend themselves to some meaningful conclusions concerning the relative magnitudes of risk associated with various shipment characteristics. For example, incident-free risk tends to dominate the overall radiological risk associated with spent nuclear fuel shipments based on this case study. Also, although comparisons between radiological and non-radiological impacts are not always advisable due to differences between acute and long-term health effects, it is apparent that non-radiological safety considerations are a significant aspect of overall operational safety involving the shipment of spent nuclear fuel.

Within the incident-free radiological risk computations, as shown in Table 13, the significance of various factors in contributing to incident-free risk vary by O/D. Handling risk is also an important element of incident-free exposure for intermodal shipments due to the transfer activity required. Radiological accident risk statistics as presented in Table 14 consistently show ground and resuspension exposure as the primary components of overall risk.

Although the case study analyses were not designed for cross-modal comparisons, the results presented in Tables 13 through 15 on a per shipment basis do provide some insight into ***amount of material*** as a mode choice consideration. Depending on the size of the campaign, considerations could include the use of different casks (e.g., rail versus truck), the number of casks per shipment, and the number of shipments. For Radtran 4-based incident-free risk, the relationship is linear for both number of casks per shipment and number of shipments. For radiological accident risk, the number of shipments has a linear effect on the risk, whereas the effect of number of casks per shipment is reflected in the severity array and would require additional analyses to establish actual relationships; assuming linearity in this instance would provide conservative results. The data also show, however, that characteristics of certain routes within each mode may vary enough that the influence of amount of material could be a site-specific consideration.

Table 13. Variation of incident-free risk values (person-rems) by O/D.

Factor	Origin / Destination Pair 1	Pair 2	Pair 3	Pair 4	Pair 5	Pair 6	Pair 7	Pair 8	All Pairs*
Crew									
mean	9.68E-03	2.27E-02	3.30E-02	4.67E-02	3.64E-02	6.14E-02	6.74E-02	1.27E-01	5.05E-02
min (% of mean)	4.18	1.79	1.23	0.87	4.73	3.65	2.86	3.67	2.87
max.(% of mean)	217.46	177.15	170.12	189.14	220.97	240.10	261.31	270.91	218.39
Handlings									
mean	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.08E-02	1.08E-02	8.84E-03	8.84E-03	4.91E-03
min (% of mean)	n/a	n/a	n/a	n/a	0.00	0.00	0.00	0.00	0.00
max.(% of mean)	n/a	n/a	n/a	n/a	450.00	450.00	550.00	550.00	500.00
Off-Link									
mean	9.46E-04	3.47E-03	1.25E-02	7.72E-03	3.97E-03	1.95E-02	1.42E-02	2.02E-02	1.03E-02
min (% of mean)	17.65	0.29	7.42	8.72	19.03	3.44	16.33	10.89	10.47
max.(% of mean)	221.14	259.34	220.19	213.20	216.69	223.97	187.15	180.64	215.29
On-Link									
mean	2.61E-03	3.97E-03	3.67E-03	5.80E-03	3.96E-03	1.11E-02	8.33E-03	1.41E-02	6.70E-03
min (% of mean)	0.00	0.00	0.00	0.00	0.36	5.59	0.92	5.19	1.51
max.(% of mean)	228.51	272.89	292.20	283.77	418.88	351.99	407.16	503.52	344.87
Stop									
mean	7.63E-03	1.19E-02	1.96E-02	2.96E-02	2.30E-02	3.96E-02	4.88E-02	9.27E-02	3.41E-02
min (% of mean)	23.32	14.67	8.87	6.21	38.45	38.68	41.55	48.14	27.49
max.(% of mean)	245.21	189.26	214.12	202.66	173.95	160.14	155.75	156.25	187.17
Total									
mean	2.09E-02	4.20E-02	6.88E-02	8.98E-02	7.82E-02	1.42E-01	1.48E-01	2.63E-01	1.07E-01
min (% of mean)	13.72	5.14	43.17	4.56	28.89	22.99	31.92	32.91	22.91
max.(% of mean)	201.13	153.08	167.02	158.29	160.44	163.35	188.74	213.89	175.74
No. of Cases:	6	6	5	8	9	9	11	11	8

* The statistics in this column were derived by treating each pair as a single observation. The mean, min., and max. values represent averages of the statistics presented in the first eight columns of this table.

Table 14. Variation of radiological accident risk values (person-rems) by O/D.

Factor	Pair 1	Pair 2	Pair 3	Pair 4	Pair 5	Pair 6	Pair 7	Pair 8	All Pairs*
				Origin / Destination					
Ground									
mean	1.22E-04	5.07E-04	9.53E-04	1.17E-03	7.24E-04	2.52E-03	2.43E-03	3.37E-03	1.48E-03
min (% of mean)	6.61	0.02	4.55	6.22	5.10	1.12	7.27	3.58	4.31
max.(% of mean)	230.36	359.00	273.08	265.31	220.57	272.[illegible]	218.90	204.50	255.49
Inhalation									
mean	1.83E-05	6.30E-05	1.29E-04	1.43E-04	9.15E-05	2.87E-04	3.00E-04	3.97E-04	1.79E-04
min (% of mean)	6.93	0.03	5.33	8.02	6.36	1.54	9.30	4.80	5.29
max.(% of mean)	227.02	320.86	225.27	241.08	193.29	264.01	197.19	192.52	232.65
Resuspension									
mean	7.95E-05	2.72E-04	5.56E-04	6.19E-04	3.64E-04	1.24E-03	1.26E-03	1.71E-03	7.62E-04
min (% of mean)	6.98	0.03	5.37	8.09	6.98	1.56	9.67	4.86	5.44
max.(% of mean)	227.70	319.43	224.09	240.36	209.47	264.31	202.32	192.14	234.98
Cloudshine									
mean	7.66E-09	2.96E-08	5.87E-08	7.06E-08	4.36E-08	1.50E-07	1.46E-07	1.97E-07	8.78E-08
min (% of mean)	5.96	0.02	4.19	5.82	4.79	1.05	6.86	3.46	4.02
max.(% of mean)	217.44	364.59	262.85	261.38	216.95	270.32	216.60	206.95	252.14
Total									
mean	2.20E-04	8.42E-04	1.64E-03	1.94E-03	1.17E-03	4.04E-03	3.99E-03	5.57E-03	2.43E-03
min (% of mean)	6.77	0.03	4.89	6.95	5.80	1.[illegible]	8.20	4.00	4.74
max.(% of mean)	203.47	343.37	252.61	255.59	216.43	269.[illegible]	212.52	196.50	243.71
No. of Cases:	6	6	5	8	9	9	11	11	8

* The statistics in this column were derived by treating each pair as a single observation. The mean, min., and max. values represent averages of the statistics presented in the first eight columns of this table.

* Where manifest and dedicated route values are identical only one was used in the calculation of the mean.

Table 15. Variation of non-radiological accident risk values (fatalities) by O/D.

Factor	Origin / Destination Pair 1	Pair 2	Pair 3	Pair 4	Pair 5	Pair 6	Pair 7	Pair 8	All Pairs*
Total									
mean	4.88E-05	7.36E-05	1.99E-04	4.85E-04	3.39E-04	7.84E-04	9.08E-04	1.67E-03	5.63E-04
min (% of mean)	10.92	12.55	8.72	6.02	7.24	5.86	6.69	6.87	8.11
max.(% of mean)	481.79	493.26	407.29	407.08	369.97	400.03	324.48	317.43	400.17
No. of Cases:	6	6	5	8	9	9	11	11	8

* The statistics in this column were derived by treating each pair as a single observation. The mean, min., and max. values represent averages of the statistics presented in the first eight columns of this table.

6.3 Radiological Risk Model Estimation

The previous discussion has demonstrated that data on primary factor values and associated risks can be collected and derived. Furthermore, there is reason to believe that both primary factor values and associated risks will fluctuate considerably by mode and route for each O/D.

In an effort to investigate the relationship between primary factors and radiological risks more thoroughly, the case study sample data was used to estimate model coefficients for the fundamental equations, presented in Chapter 5 by mode. This process had two basic objectives: (1) to test the statistical confidence with which each previously identified factor contributes to incident-free and radiological risk, respectively, and (2) to allow for subsequent conduct of sensitivity analyses to ascertain the relative importance of primary factors in determining these risks.

For the sake of brevity, the model estimation process is described separately in Appendix H. As noted by the results of the statistical tests applied to the model estimates, the model specifications exhibit a good overall fit with the observed data, and the coefficient estimates associated with each term (comprised of primary factors) are significant with rare exceptions. Thus, the equations developed in Chapter 5 represent the relationship between primary factors and risk estimates based upon statistical data generated by the case sample.

6.4 Sensitivity Analysis

The purpose of a sensitivity analysis is to provide a basis for evaluating the stability of the relationship between primary factors and radiological risks across a wide range of factor inputs. Sensitivity analyses are typically performed in recognition of the uncertainties in the assessment process that are introduced by assumptions inherent in the data inputs, methods used to calculate risks, and development of the fundamental physical relationships.

The preferred approach would be to vary each primary factor value one at a time and rerun the Radtran 4 assessment for every case in the sample. Because sufficient resources were unavailable to perform sensitivity analyses at this level of detail, the estimated model coefficients (see Appendix H) were used to obtain a general idea of the relative influence of primary factors on radiological risk.

The sensitivity study was performed on each model by increasing each primary factor (e.g., shipment duration) by 10 percent and recalculating the associated incident-free and radiological accident risks. The factors were adjusted one at a time to determine their singular effects. Table 16 presents the results of this effort. The first two columns show the primary factors evaluated by mode. Each of these factors was increased by 10 percent, as indicated in the third column. The last two columns show the percent increase in the risk caused by the 10 percent increase in the factor values.

For the highway and rail modes, radiological accident risks change at a disproportionately higher rate in comparison with changes in primary factor values. This suggests that emphasis should be placed on reducing accident rate, trip length, and general population exposure when shipping via highway and rail modes.

Trip duration has the largest effect on the incident-free risk of all the factors. This is probably a result of the fact that so many of the incident-free risk component terms include trip duration, such that it has multiple effects on overall incident-free risk. Average number of crew is another major factor for highway and manifest rail.

The results of the waterway and intermodal sensitivity analyses for both incident-free and radiological accident risk are inconclusive. This may be due to the small sample sizes that affected the statistical confidence of the model estimates from which the sensitivity analysis was performed.

Table 16. Sensitivity analysis.

Mode	Variable Changed	% of Increase in variable	% of Increase in Incident Free Risk	% of Increase in Radiological Accident Risk
Highway				
	Nc - Average number of crew	10.00	4.66	
	tl - Average trip duration	10.00	7.96	
	T - Average traffic density	10.00	1.51	
	L - Average route length	10.00	1.68	12.86
	p - Average population density	10.00	0.13	12.86
	Sa - Average mean accident rate	10.00		12.86
Manifest				
	Nc - Average number of crew	10.00	3.02	
	tl - Average trip duration	10.00	4.64	
	T - Average traffic density	10.00	+0.00	
	L - Average route length	10.00	3.61	10.60
	p - Average population density	10.00	1.62	10.60
	Sa - Average mean accident rate	10.00		10.60
Dedicated				
	Nc - Average number of crew	10.00	0.34	
	tl - Average trip duration	10.00	5.24	
	T - Average traffic density	10.00	0.17	
	L - Average route length	10.00	3.48	10.60
	p - Average population density	10.00	4.55	10.60
	Sa - Average mean accident rate	10.00		10.60
Waterway				
	Nc - Average number of crew	10.00	+0.00	
	tl - Average trip duration	10.00	7.26	
	T - Average traffic density	10.00	0.00	
	L - Average route length	10.00	0.04	2.77
	p - Average population density	10.00	7.26	2.77
	Sa - Average mean accident rate	10.00		2.77
Intermodal				
	Nc - Average number of crew	10.00	0.33	
	tl - Average trip duration	10.00	1.94	
	T - Average traffic density	10.00	0.03	
	L - Average route length	10.00	3.33	8.19
	p - Average population density	10.00	1.54	8.19
	Sa - Average mean accident rate	10.00		8.19

6.5 Emergency Response and Environment

As noted in Section 5.3, emergency response and sensitive environmental areas were not explicitly addressed in the formal risk model specifications. These factors can, however, be derived independently and included in an overall impact matrix for evaluating mode and route alternatives.

To illustrate this aproach, the case study did consider average response distance from DOE response facilities as a surrogate measure for emergency response coverage. The data collection approach is described in Appendix G. Average response distance for each case study route was subsequently compared to radiological accident risk and its associated factors, namely route length and population density.

Table 17 presents a correlation matrix by mode of average emergency response distance, radiological accident risk (RAR), trip length, and population density. The values in all cases are negative and relatively low. This suggests there may be a slight inverse relationship between qualified emergency response coverage and RAR. This suggests that a slight degradation in emergency response capability is likely as one moves further away from population centers and as trip lengths increase (presumably going into more rural areas).

Table 17. Correlation of emergency response with radiological accident risk (RAR).

Measure	Highway	Rail	Waterway	Intermodal
Average route length	-.154	-.180	-.346	-.117
Average population density	-.047	-.216	-.542	-.353
RAR	-.093	-.177	-.254	-.238

This finding is somewhat troubling since the ability to provide adequate emergency response may be compromised when a supposedly "lower risk" route is specified. This tradeoff needs to be considered either by influencing the routing decision or identifying locations where improvements in response coverage are needed. Although not analyzed here, it is expected that exposure to environmentally sensitive areas may also increase with lower population exposure and longer trip distances.

6.6 Case Study Analysis Summary

This case study was designed to (1) explore the ease with which primary factor values and risk estimates can be derived for mode/route combinations, (2) assess the variation in primary factor values and risk estimates for each mode/route, and (3) evaluate the interaction among primary factors and their statistical significance in determining the risks to different segments of the population.

Findings related to these objectives are summarized below. These conclusions should be reviewed in the context of the analysis environment used in the case study. The extent to which representations inherent in HazTrans, Radtran 4, and the overall methodology affect generalization of these findings should be taken into consideration.

6.6.1 Ease of Developing Primary Factor and Risk Values. The case study clearly demonstrates that information describing primary factors can be assembled and that quantifiable measures of these values can be developed. In some instances, the methods used to develop factor values must rely on surrogate measures that have established validity based on prior studies.

6.6.2 Variations in Primary Factor Values and Risk Estimates. Variations in primary factor values and corresponding risk estimates are expected if primary factors are discerning factors in determining preferred routes. The case study results demonstrate that primary factor values fluctuate considerably across mode, route, and O/D. Similar variations were experienced in corresponding radiological and non-radiological risk values.

It is evident from these results that primary factor values can be expected to change considerably by mode and route for different shipment lengths, shipment types, and locations in the United States. This underscores the need to evaluate those mode and route factors that significantly impact public safety.

6.6.3 Interaction of Primary Factors and Risks. Incident-free risk tends to dominate the overall radiological risk associated with spent fuel shipments; in most instances, incident-free risk is much larger than radiological accident risk. The significance of various factors in contributing to incident-free risk varies by O/D. Ground and resuspension exposures, however, are consistently the primary components of radiological accident risk. It is also apparent that non-radiological safety considerations are a significant aspect of spent fuel shipment safety.

Results of the sensitivity analysis indicate that radiological accident risk is strongly influenced by population, exposure, trip length, and accident rate for highway and rail operations. Trip duration has the most profound effect on incident-free risk, although the other primary factors are also significant contributors.

A preliminary evaluation of emergency response coverage suggests that a slight inverse relationship may exist between qualified emergency response and radiological accident risk. Some degradation in emergency response coverage appears to occur as shipments move further away from population centers and as trip lengths increase. If adequate emergency response could be compromised as supposedly lower risk routes are identified, this trade-off needs to be taken into consideration in mode and route selection.

The risk results also provide insight into amount of material as a primary factor for mode choice consideration. The payload size, cask capacity, and number of casks per shipment are interrelated in this regard. On a single cask per shipment basis, the case study results indicate that characteristics of certain routes within each mode may vary enough that the influence of amount of material may be a consideration specific to each O/D pair.

7.0. Overall Assessment of Primary Mode/Route Selection Factors

An overall assessment of the primary mode/route factors identified in this study is presented below. Following a brief overview of the background and approach used to select a set of primary factors, each primary factor is discussed in detail.

7.1. Summary of Identification and Selection of Primary Mode/Route Factors

Generally, the selection of both mode and route by shippers and carriers has been based largely on operating efficiency, customer service needs, and economics. Increasingly, shippers of all hazardous materials, including high-level radioactive waste and spent nuclear fuel, have become more attuned to the need to carefully assess the relative safety of each mode before making a selection. Hazardous material carriers, especially for radioactive materials, have been subject to various Federal and State requirements on routing for the last decade. More and more carriers, however, recognize their own responsibility for ensuring that the safest routes are chosen (within the regulatory guidelines) for these shipments. Both shippers and carriers would benefit from the identification of a common set of mode and route selection factors.

The first approach employed in this study was a hierarchical approach that was based on the most important mode/route factors through a review of all factors that had previously been considered or proposed as important for selecting modes or routes. To ensure that all viewpoints would be considered, a comprehensive candidate list of factors was developed. Each factor was qualitatively evaluated in terms of criteria such as impact on safety, interrelationships among the factors, measurability, and feasibility of implementation. This qualitative evaluation resulted in several important findings:

- Mode and route factors are difficult to evaluate separately. They must be considered together and then compared with other mode/route combinations.

- The only separable mode choice factors found were cask availability, mode accessibility, and amount of material to be shipped. Cask availability and mode accessibility can be eliminated as modal barriers over the long term. Amount of material is perhaps the single most important factor in mode selection because it directly impacts the number of shipments required and tends to favor rail and barge because of substantially higher cask payloads.

- There are many legitimate mode/route factors. The validity and importance of each factor is ultimately dependent upon the level of analysis to be conducted.

- A hierarchy of mode/route factors can serve as a decision-making tool to help shippers and carriers. The hierarchy allows the analyst to see the relationships and interdependencies among the many potential factors.

- A hierarchy allows the analyst to adjust for the level of analysis to be conducted. The factors at the highest end of the hierarchy are at a level of detail suitable for a national level of mode and route analysis. The lower end of the hierarchy is more suitable for a State or local level of analysis.

The hierarchical approach used by the project team led to the identification of eight primary mode/route selection factors that are identified as primary mode/route selection factors. These factors include general population exposure, occupational population exposure, environmental exposure, accident rate, shipment duration, trip length, emergency response, and amount of material. These eight factors are believed to be the most suitable as national-level mode/route selection factors.

The second approach used in this study was to develop models showing the relationships of various factors in estimating the risk of transporting radioactive materials. Fundamental physical relationships were established in these models. Important components from the models were then extracted in order to identify important factors that contribute to each component of risk. The factors developed in the risk modeling were shown to be consistent with the primary factors identified using the hierarchical approach.

A case study was developed with multiple origins and destinations and representative routes. The case study helped to examine the following important elements of mode/route selection: the variability of factors and corresponding risks from mode to mode and route to route, the feasibility of measuring and evaluating the primary factors, and the nature and type of relationship between each primary factor and the three risk components of the project definition of public safety.

7.2. Evaluation of Primary Mode/Route Factors

The framework for conducting the overall evaluation of factors included the following criteria: (1) the nature and degree of impact on public safety, (2) the degree of variability from mode to mode and route to route, (3) the ability to measure, and (4) the feasibility of implementation. *Ability to measure* involves the degree of confidence in the representativeness of the factor, its degree of accuracy, and the difficulty of measuring it. *Feasibility of implementation* involves the relative difficulty of obtaining the required information and the related institutional and political considerations. The purpose of the overall evaluation of factors is to bring together the results of all the analyses conducted in this project relative to each primary factor.

7.2.1. General Population Exposed. This primary factor includes people along the route of travel who are at risk from the transportation of high-level radioactive waste and spent nuclear fuel. Population along the route has a direct effect on two components of the project definition of public safety: incident-free exposure from normal transportation and potential exposure to the release of radioactive material resulting from a severe accident. The relationship between population and these two measures of public safety is direct. The greater the population along the route of travel, the greater the potential for incident-free exposure and the greater the potential for a radiological release to have human health consequences. All other things equal, the mode or route that involves the lowest population would be the safest route. Of course, all other things are not usually equal, and population has to be considered in context with other factors.

Incident-free exposure to the general population depends on the total number of people potentially affected, the proximity of the people to the route of travel, and the time of exposure. Results from the case study indicate that the general population (on-link and off-link) incident-free risk is much lower than occupational risk for all modes. The one exception to this is the exposure during stops. In previous quantitative risk studies, incident-free exposure to the general public has been estimated to be low. As the distance from the radioactive material increases, the potential health effects fall off dramatically. In most cases, people in the "general population" category are hundreds to thousands of feet from the right-of-way. Nevertheless, it is important to take the population within a reasonable distance from the right-of-way into consideration when selecting a mode or route of travel.

The number of people in proximity of the right-of-way is also important in measuring radiological accident risk. If there is an accident severe enough to cause a release of material, the population exposed would depend on the size of release and the speed and direction of the wind. The location and specific population affected by such an accident would be very difficult to predict. From a route and mode comparison standpoint, the only variable that could be measured would be the population within a certain bandwidth of the right-of-way that could be subject to exposure from such an accident. If a release-causing accident did occur, the general population along the route would be likely to have a much greater potential exposure than occupational workers because of the greater number of people in this category potentially at risk.

There is little question that population should be included as a mode/route factor. The real question is how best to account for it. Ideally, one would count all individuals within a certain bandwidth along a right-of-way and compare from one route to another as the measure of population. This would include people in all three categories of general population identified in the incident-free hierarchy in Table 4: residential, non-residential, and special. One would count all people who resided within the bandwidth as well as all the people at work, all of the pedestrians, all of those in other vehicles (shared-facility users), tourists, and all those in facilities such as hospitals, schools, and prisons and people at special events. All of these are legitimate segments of people who should be counted in order to arrive at an exact population count.

Obviously, an actual count cannot be done for every potential mode or route decision by a shipper or carrier. The next best approach would be to make general estimates for each of the most important components of population: residential, employment, traffic density, and number and size of special facilities. Most of this information is available or can be derived from other data available at the local level. This may be feasible for detailed route assessments for short distances. For longer distance shipments and for considering a variety of routes and modes, however, the only feasible measure is the census population.

With the availability of the Census Bureau population data, the ability to measure residential population along any route is very good. This information is available in spatial (geocoded) form, and can be overlaid as bandwidth of population density on the routes under consideration to obtain the necessary exposed population. Although Census Bureau population data are limited to residential population, the number of potentially exposed people obtained from this information can be considered representative of the entire population along the route, particularly at the primary factor level. Limitations to this approach include the over-representation of employment population in urban areas and over-representation of residential populations in suburban areas during different times of the day, week, and year. Because these variations are dynamic and time-dependent, it is impractical to determine a more accurate representation of the number of people potentially exposed on any but the most microscopic level of analysis. Obtaining such information would be extremely time consuming and resource-intensive for more than a single jurisdictional area.

In the past, the ability to collect this information has been limited. Counting people along different routes, particularly the longer routes, has been cost prohibitive. The availability to shippers and carriers of off-the-shelf geographic information systems (GIS) that use Census population data, either directly or indirectly, has increased, however. These systems can now be used to obtain population counts and exposures along all definable modes/routes.

In addition to having a significant impact on public safety, population can be highly variable from route to route and mode to mode and, therefore, can be a clear route or mode discriminator. The case study results presented in Table 12 illustrate the variability of most primary factors including general population. The min-max values of the population density (surrogate measure for the general population) is very broad for each O/D pair evaluated.

Although every potential mode/route alternative must be evaluated in detail, there are a few general observations across modes that can be made. The first observation is that there are always tradeoffs involved in selecting either mode or route to minimize population. Highway offers the most flexibility to avoid large population centers because of the large number of route alternatives, although the best highways are the Interstate system highways which usually connect urban centers. Selecting highway routes to avoid major cities could have other undesirable effects such as increasing shipment duration and trip length (effects which will be discussed below). It is usually more difficult to follow a population avoidance strategy with rail because rail lines traditionally connect major cities and there are fewer alternative routes available than for highway. Barge shipments follow waterways, of course, and generally offers a low population alternative if it can be used.

In summary, the use of general population as a mode/route selection factor is highly desirable because of its direct and significant impact on public safety, because of its variability between mode/route alternatives, and because it can be reasonably well measured using readily accessible Census data.

7.2.2. Occupational Population Exposed. This factor includes workers who may be in proximity to a container at any time in the entire shipment cycle. This obviously includes transport workers, such as the crew and the container handlers. It also includes other groups who could receive exposure by nature of their occupation, such as persons in escort vehicles, security guards, inspectors and other enforcement officials, and even emergency responders. The potential exposure to the occupational population is a major consideration for safety because of the close proximity of this group to the container. It has a major effect on both incident-free risk and radiological accident risk.

Most of the support groups (handlers, security, etc.) within the occupational population receive a onetime exposure for each shipment. Handling risk is especially important for the intermodal shipments as demonstrated in the case study. The analysis showed that handling exposure can be a significant percentage of total intermodal incident-free risk and that the intermodal incident-free risk is higher than that for all other modes.

The vehicle crew receives exposure during the entire shipment cycle. Previous risk studies have found that incident-free exposure to the crew is the single largest component of the overall risk of transporting high-level radioactive waste and spent nuclear fuel. The case study results from this report support this for highway, dedicated rail, and manifest rail. Off-link population is the largest factor for waterway shipments and container handling for intermodal shipments, as noted above.

There are important differences in the components of occupational risk from mode to mode. The truck crew is much closer to the package than either the rail or barge crew for a typical shipment and, therefore, will receive a higher dose on a per-mile basis. The rail or barge movement, however, may require longer distances, which increases their exposure relative to truck. Also, there are generally more and longer stops by rail and barge. Shipment by rail usually requires at least one interchange between rail carriers. Shipments by barge usually require a modal interchange to get the cask to and from the barge loading facility. Stop times can have a significant effect on incident-free exposure.

The variability in occupational exposure is illustrated in Table 12. The surrogate measure for occupational exposure was simply the number of crew. This does not usually vary within a mode. The fact that occupational exposure can vary by route can be illustrated by considering number of crew along with shipment duration (a combination of trip length and average speed from Table 12). When the values for these two are taken together, one can see the substantial variability in occupational population exposure from one mode/route alternative to another.

The ability to measure occupational population is excellent. The number and proximity of crew and the number and proximity of package handlers are known for each mode. The number and proximity of people at stops and the duration of stops are less certain, but can be reasonably estimated based on carrier experience. Because of the predominance of the vehicle crew exposure, the best single measure that is representative of incident-free dose to the occupational population is probably the number of crew involved in the shipment.

The practicality of implementing occupational exposure as a mode/route selection factor is considered excellent. Data collection would be simple and the cost of data collection would be nominal, since carriers and shippers are already familiar with crew and handler operations.

One major philosophical issue in using occupational exposure as a mode/route selection factor is risk acceptance. It can be said that transport workers voluntarily accept the risk of exposure. On the other hand, the general public does not voluntarily accept the risk of exposure from the transport of radioactive materials. It is argued that the objective of mode/route selection should be to minimize the involuntary risk to the general population as opposed to the voluntary risk to the occupational workers. The manner in which this issue is treated could have a significant impact on mode/route selection. Past studies have shown the incident-free dose to the vehicle crew to be much larger than the cumulative dose to the surrounding population for a typical shipment. The vehicle crew dose is dependent primarily on shipment duration. If both occupational and public exposure were included together, the best mode/route alternative would usually be the shortest and most direct one in order to minimize the time of exposure to the vehicle crew. This could result in a mode/route alternative that has a much higher surrounding population than if public exposure were considered separately. Because of the significant difference in the types of exposure between public and occupational groups, it was decided to treat each one separately in this study.

In summary, occupational population is highly desirable as a mode/route factor because it is a major contributor to the overall level of incident-free exposure, it can be easily and accurately measured, and it can vary considerably by mode and route.

7.2.3. Shipment Duration. Shipment duration strongly affects the safety of radioactive material transportation because it has a direct relationship with incident-free exposure. The longer the material is in transit, the longer the exposure to the crew and the general public. This is illustrated by the incident-free risk model developed in Chapter 5 and by the results of the sensitivity analysis developed in Chapter 6 and Appendix H.

This factor is determined by the combination of many other factors, as shown in the Table 5 hierarchy. The major considerations include the route length, vehicle speed, and the number and length of both delays and stops enroute. Shipment duration is measured in units of time. In past studies, the surrogate used for shipment duration has usually been just the trip length. In some instances, this length has been combined with average vehicle speed to obtain exposure time. In others, the length has been used exclusively to compare miles of exposure or some equivalent measure. This approach has neglected the effect of stops and variations in vehicle speeds, which can vary substantially between different modes and their corresponding routes.

The ability to measure shipment duration is very good. Shippers and carriers know the estimated time required to ship material from one location to another for their own scheduling and billing. This would include reasonable estimates for planned and unplanned stops. Unforeseen delays enroute, such as weather or road conditions, create some uncertainty in the ability to estimate shipment duration.

Shipment duration can vary significantly from mode to mode and from route to route and, thus, can be a good mode/route selection discriminator. As a general rule, highway offers the fastest movement among the three modes and waterway is the slowest. Rail movements usually involve more stops enroute than highway, unless it is by dedicated rail. The case study results in Table 12 illustrate the variability of shipment duration when one combines the results for trip length and average vehicle speed.

Overall, shipment duration is a very important mode/route selection factor because it is a major determinant of incident-free risk, because it is easily measured and applied, and because it can vary from one mode/route alternative to another.

7.2.4. Accident Rate. The greater the likelihood of an accident, the greater the potential for an injury to the crew and for the release of radioactive materials and corresponding exposure to the public. Thus, accident likelihood has an important impact on the safety of transporting radioactive materials. A measure of accident likelihood is a necessary component of estimating both radiological accident risk and non-radiological accident risk. This is clearly illustrated by the risk models estimating both radiological and non-radiological accident risks in Chapter 5. The traditional measure has been derived by multiplying the number of accidents of a specified severity per unit of distance times the corresponding trip length to obtain an accident rate.

The accident rate, as a primary mode/route factor, represents many other factors that could have an influence on the likelihood of an accident. The quality, condition, and design of the highway, railway or waterway infrastructure all have an impact on the potential for an accident. The operating procedures and quality control of the carrier all have an impact on the potential for an accident, and these can vary from mode to mode. Weather and seasonal conditions have an impact. All of these subfactors are listed in the hierarchy in Table 5. Over time, the interplay of all these various components is reflected in the accident experience for each right-of-way. The accident rate is considered the best available broad measure of all these factors.

The variability of accident rates can be significant for different mode/route combinations. This is illustrated by the high variation and minimum/maximum range for accident rates for the case study results shown in Table 12. Much of the difference in accident rates by highway is reflected in the classification of the highway. The Interstate highways usually have lower accident rates because they are built to the highest design standards in terms of geometry, grade, roadway structures, guideway separation, access control, etc. The accident rates of various Interstate highway segments, however, can be significantly different and some non-Interstate highways can have lower accident rates than the Interstates.

The ability to measure this factor is excellent at a gross level of analysis, but becomes more difficult for a more detailed level of analysis. Accident rates are available at different levels of specificity and quality. National averages are available for different highway classifications. Average waterway accident rates are available for specific water systems, such as the Mississippi River system. These national averages may be sufficient at the primary factor level. The use of national, or even regional, accident rates, however, may not be sufficient to differentiate between route or mode alternatives. The more specific the accident rate is to the road, rail or water segment of interest the better. Some segment specific accident rates for highway and rail are available in some routing models today. The quality and uniformity of accident data can also vary from State to State. The analyst should be careful to use the best available and most consistent data.

Accident rates (accidents/train-mile or car-mile) for rail are generally proprietary information and unavailable outside the owning railroad. The accident rates are reflected, in general, by the classification of the track. Specific rail link accident rates by track-class are not publicly available because data on traffic volumes for links are protected information. Accident rate data can be developed by flowing shipment data (such as the 1 percent Waybill sample) over the rail network and combining it with FRA accident data by node and link. Large data bases have been developed by consulting organizations using this approach.

The type of accident rate employed is also important. Generally, the accident rate that reflects the most severe types of accidents is preferred since only the most severe accidents could result in a release from the casks used to transport high-level radioactive waste and spent nuclear fuel. In most cases, this will be the fatal or injury-producing accident rates as opposed to the overall vehicular accident rate. Also, the accident rate that most closely represents the type of operation of interest is preferred. This would be the high-level radioactive waste/spent nuclear fuel motor vehicle accident rate for highway. Unfortunately, this level of specificity is not found in accident statistics. The best accident rate that is most often available is the general truck driver fatal accident rate.

The practicality of using accident rates as a mode/route selection factor depends on the level of analysis. If the analysis is national or regional, where national average accident rates can be used, then carriers and shippers will have little difficulty in implementing the criterion. As the level of analysis becomes more local in nature, the availability and cost of data become much more difficult.

In summary, the accident rate is a necessary mode/route selection factor. It is needed to provide an estimate of the likelihood of an accident for both radiological and non-radiological accident risk. It is broadly representative of other numerous factors that influence accident likelihood. It is also relatively easy to measure since the accident histories of the mode or route under consideration are usually available, although one must exercise care in the type and quality of data to be used.

7.2.5. Trip Length. Trip length affects all three components of public safety: incident-free risk, radiological accident risk, and non-radiological accident risk. It affects incident-free risk because it is a major component of shipment duration. It affects both radiological and non-radiological accident risk because it is a component of the accident rate. All other things equal, the shorter the trip the lower the incident-free exposure and accident risk.

The major tradeoff for trip length is, of course, population and sensitive environments. The most direct route may be the one through the highest population areas or the greatest number of environmentally sensitive areas.

The ability to measure trip length is simple and straightforward. Most of the highway, rail, and waterway distance references are now readily available on software. Trip length can obviously vary substantially by mode and by route between almost all origins and destinations. This is shown in Table 12 for the sample set of routes selected for the case study.

7.2.6. Environment. This factor is related to public safety in that a radiological release resulting from an accident could have significant adverse impacts on sensitive environmental areas located close to the right-of-way. Contamination of sensitive environments, such as major drinking water reservoirs, could have direct public health consequences.

This is a factor that has not traditionally been considered in most previous routing and environmental studies relating to radioactive material transportation. A comprehensive treatment of all potential public safety impacts from mode and route selection, however, requires that sensitive environmental areas be included. The question to be addressed is what constitutes a "sensitive environmental area?" Some would argue that every water source, including all streams, rivers, ponds, and lakes should be considered sensitive to radioactive material releases. Some argue that all agricultural lands should be considered sensitive since contamination would potentially enter the human food chain.

Although there are good arguments that contamination of such broad measures as bodies of water and agricultural land do relate to public safety, they would be of little use as mode or route discriminators since virtually every mode and route crosses some body of water or travels through some agricultural area.

There was a wide difference of opinion among the TAG on the inclusion of environment as a mode/route factor. There did seem to be some agreement that if it was to be included as a factor, that it be limited to something that could reasonably be measured and that could actually vary among routes. The initial definition that was arrived at was a designated area that had been set aside by an official agency for some special reason, such as drinking water reservoirs, wetlands, or refuges. Sacred Indian tribal grounds was added as another possibility. It was agreed that the definition of "sensitive environments" for the purposes of differentiating mode/route alternatives needs to be assessed in greater detail.

Once the sensitive environment has been defined, another question is how to measure it. Should evaluation of the mode/route alternative be based on the total number of areas crossed? On the average distance from sensitive areas? On the total square footage of the sensitive areas within a certain bandwidth? Again, this is an area that has not been intensively studied.

Environmental exposure was one of the primary factors that was not evaluated in the case study for this project. The ability to measure and the feasibility to implement are also uncertain without some kind of assessment. Initially, the cost and difficulty of data collection would be very high.

In summary, environment is believed to be an important mode/route selection factor because environmental contamination can impact public safety. Its usefulness as a mode/route discriminator, however, is somewhat questionable depending on the unit of measure. The variability of this factor and its interrelationship with other mode/route factors needs to be more intensively studied.

7.2.7 Emergency Response. The relationship of emergency response to public safety is the potential mitigation of the consequences of an accidental release of radioactive material in transit. The extent of mitigation is difficult, if not impossible, to predict or measure. Nevertheless, emergency preparedness and response is considered an integral component of the overall system for safe transport of radioactive materials, and it is desirable to be able to account for it in mode/route selection. Response to a radioactive material release is much more sophisticated than that for most other emergencies and requires specialized training. Consequently, the greater the proximity or availability of *trained* responders to a mode/route alternative, the more desirable it is.

This is another factor that has not been evaluated in much detail in terms of route or mode selection in the past. It is included as a secondary factor for the U.S. DOT routing guidelines for general hazardous materials. There are many facets to emergency response, and there was considerable discussion of this factor by the TAG. Two major facets of emergency response relative to mode/route choice came out of the discussion: proximity and capability. The first important element is the location of responders relative to the route of travel. How long would it take for responders to arrive at the scene of a transportation accident involving a release of radioactive material? The second major consideration is the level of capability—training and equipment. The consensus of the TAG seemed to be that the measure for emergency response should be based on the time to respond for specially trained emergency responders, not just first responders. "Specially trained" responders were equated to be the DOE radiological response teams.

Currently, the required response time for qualified responders can be determined using existing software packages that incorporate routing algorithms. The number of qualified responders are limited, and their capabilities and locations can be geocoded into these packages. First responders consist primarily of local fire departments and law enforcement agencies. The feasibility and cost of obtaining the necessary information to include these members in the evaluation would be prohibitive. Therefore, the measure for this factor is recommended to be the maximum amount of time for a *qualified* responder to arrive at any point along the potential route of travel.

The ability to measure emergency response would actually be good using the above unit of measure. As mentioned, computerized routing routines can obtain the maximum time from a qualified responder to any point on a network. The use of these routines requires the acquisition of the software and the knowledge of how to use it. The location of the responders is available from the appropriate Federal agency and from most potential shippers.

The variability of emergency response from one mode/route alternative to another is difficult to assess since it has not been evaluated to any degree in the past. This factor could also be relatively difficult to implement since the cost of the data or software could be high. An attempt was made in the case study to evaluate the variability in this factor, and the results were included in Table 12. Based upon these preliminary results, it appears that emergency response could vary significantly from mode to mode and route to route.

In summary, emergency response is believed to be an important consideration for mode/route selection because it could reduce radiological accident consequences. Its value, however, would depend on agreement on a suitable unit of measure that is reasonably accessible and cost effective.

7.2.8 Amount of Material. The amount of material to be shipped has a direct impact on all three components of the project definition of public safety. As has been discussed previously, it will determine the total number of shipments that will be required. Since the payload of a rail cask is four to seven times that of a highway cask, it would take four to seven times as many shipments to move the same amount of material by highway as by rail. This would entail roughly four to seven times the incident-free exposure, radiological and non-radiological accident risk to ship by highway for the same amount of material. This factor, by itself, would heavily favor the rail mode (or barge using rail casks) over the highway mode. The case study analysis, however, illustrates that the analyst must still conduct a careful evaluation of both modal alternatives to ensure the relative safety of a particular mode, even considering the cask payload differential.

The variability of this factor is substantial from mode to mode because of the difference in cask payload. The ability to measure is obviously excellent since the quantity to be shipped has to be known by the shipper and the difficulty of data collection is low.

7.3. Summary Assessment of Primary Mode/Route Factors

Table 18 identifies each of the primary mode/route factors and summarizes the results of the overall assessment of each factor. These factors are identified as the most important for consideration by shippers and carriers in selecting modes and routes for shipping high-level radioactive waste and spent nuclear fuel.

No attempt has been made to weight these factors or combine them into an easy-to-use formula. As stated in the introduction, the primary purpose of this study, as directed by Section 15 of HMTUSA, was to *identify* important factors and to assess their *degree of impact* on public safety. This study, however, does provide information on the manner in which these factors contribute to the risk of transporting radioactive materials. This can serve as a basis for the way that these factors are combined to make mode/route decisions.

Table 18. Overall assessment of primary factors.

Factor	Relationship to Public Safety Component	Degree of Impact on Overall Public Safety	Variability	Ability to Measure	Feasibility to Implement
General Population Exposed	Affects incident-free exposure and radiological accident risk	Major factor for radiological accident risk. Contributes to incident-free risk, but much lower than occupational exposure. People at stops represent biggest risk from incident-free exposure within general population.	Can vary substantially by mode and route	Excellent for residential; poor to good for others	Data collection moderately difficult
Occupational Population Exposed	Affects incident-free exposure and radiological accident risk	Largest component of total incident-free risk because of crew for all modes.	Varies substantially by mode because of crew and by route because of shipment duration	Excellent	Data collection easy; "risk acceptance" issue
Shipment Duration	Affects incident-free exposure	Major impact on incident-free risk; influences times of exposure for both general and occupational populations.	Can vary substantially by mode and route	Excellent	Data collection easy; compliance easy
Accident Rate	Affects radiological accident risk and non-radiological accident risk	Major component of estimating probability of radiological and non-radiological accidents.	Can vary by mode and route	Fair to excellent	Data collection moderately difficult; quality of data can be a problem
Trip Length	Affects incident-free risk, radiological accident risk and non-radiological accident risk	Major impact on shipment duration, which influences incident-free risk. Major component of accident rate, which influences radiological and non-radiological accident rate.	Can vary substantially by mode and route	Excellent	Data collection easy
Environment	Could be significantly affected by radiological accident risk	Radiological accident release could contaminate sensitive areas, causing human health consequences.	Uncertain, not evaluated in case study	Difficult, but depends on unit of measure	Data collection difficult; compliance difficult; depends on definition of units
Emergency Response	Affects radiological accident risk	Can reduce accident consequences from radiological accident releases.	Difficult to estimate	Depends on unit of measure	Data collection difficult; compliance difficult
Amount of Material	Affects all three public safety components	Affects mode selection because of difference in cask payload and resulting number of shipments required.	Number of shipments varies substantially by mode	Excellent	Data collection easy; cask availability problem

8.0. References

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Appendix A

Definitions

Appendix A. Definitions

Dedicated Rail

Usually considered to be a subset of regular train service characterized by homogeneity of the cargo. This term includes both unit trains and scheduled high-speed trains, such as those hauling trailers and/or containers on flatcars (TOFC/COFC). As used in this study, the term "dedicated train" refers to a relatively short unit train operated exclusively for the transportation of high-level radioactive materials.

Hazard

The term refers to the potential occurrence of an injurious event or accident. "Hazard" is not the same as "risk" because the latter also incorporates the consequences of an accident should it occur.

High-Level Radioactive Materials

Spent nuclear fuel (SNF) is irradiated fuel discharged from a nuclear reactor, either a commercial power plant, one operated by government-sponsored R&D programs and universities, or one that powers a naval vessel. High-level radioactive waste (HLW) results from the reprocessing of spent nuclear fuel, a step in either the production of nuclear weapons, the program to recycle commercial spent fuel (now inactive), or the reprocessing of naval reactor fuel. The types and amounts of these materials tracked by DOE in the Integrated Data Base, plus naval reactor shipments, are assumed to be the universe of cargoes that will need to be transported eventually.* (High-activity activation wastes from reactor decommissioning are excluded.)

Incident-Free Risk

Incident-free risk refers to the risk to people resulting from the radiation that is normally emitted during transportation not resulting from an incident that would cause an unintentional release. Even heavily shielded, radioactive materials emit small amounts of radiation. The levels of this radiation are regulated by cognizant Federal agencies.

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* U.S. DOE, "Integrated Data Base for 1991: U.S. Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics."

Manifest (Regular) Train

As used in this study, "regular train" refers to any of the types of trains other than dedicated trains that could be expected to handle a portion of the movement of a cask car from origin to destination. A regular train would typically be a lower priority, advertised freight service, or "manifest" train in general service containing a mixture of commodities that may include grain, automobiles, building materials, explosives, flammables, and other hazardous materials. Operation would be in accordance with "operational restrictions" as defined below.

Non-radiological Risk

This category covers those risks associated with transportable hazards that have nothing to do with exposure to radiation. The risk pertains to occupants of highway vehicles, train crews in grade crossing accidents, and pedestrians struck by trains. Others who might be impacted by non-radiological risk include those affected by other train accidents, protesters and security personnel, and casualties of evacuations and other emergency response operations.

Operational Restrictions (Rail)

For the purposes of this study, it is assumed that both dedicated trains and regular trains may be operated under similar restrictions, derived from both the DOD/DOE shipping instructions for naval reactor spent fuel shipments and current Association of American Railroad (AAR) guidelines, as follows:

- Maximum speed is limited to 35 mph
- One train is stopped (stands) during passes while the other moves past at no more than 35 mph (AAR only)
- Cask car must be placed at the rear of the train (DOD only).

Radiological Risk

Radiological risk refers to the risk to people voluntarily (transport workers and emergency responders) and involuntarily (the public) exposed to radiation from sources contained within casks, as well as material released from them. Non-accident (incident-free) risk is that associated with the radiation that always emanates from the loaded cask, sometimes called normal radiation. Accident risk is that associated with radioactive material released from a damaged cask, as well as exposure to radiation from a cask, perhaps heightened by damage, during response operations. Radiological risk is typically quantified in terms of person-rems, which is a combination of the number of people exposed and the health effects of individual exposure (i.e., type, intensity, and duration of radiation and manner in which the individual is affected). In this report, risk is usually referred to on a per cask-mile basis, which is the risk associated with the transport of one cask one mile. A conversion factor of 2500 person-rem per expected fatality is used. Affected populations include crews and other personnel, on-board escorts and others accompanying a shipment, inspectors, the populace along the route of travel, and emergency responders. Radiological effects on plants and animals were not considered in this study.

Risk

Risk typically refers to a combination of the likelihood that an injurious event or accident will occur and the consequences should it occur. Risk analysts define risk as the product of the probability and consequences of an accident, weighted equally. Implicit in this definition is the presumption that probability is as important as the consequences. In contrast, those responsible for public safety often discount the likelihood (probability) and focus on the potential consequences.

Safety

Because this study recognizes that safety is not absolute, the focus is on safety, as is the *relative* freedom from risk afforded by the available transport modes. Safety concerns acknowledged and addressed by this study include

- Radiological effects of normal incident-free transport
- Radiological effects of accidents during transport
- Non-radiological deaths and injuries from accidents during transport.

Appendix B

Invitees to and Attendees at Mode/Route Technical Advisory Group Meeting

Appendix B. Invitees to and Attendees at Mode/Route Technical Advisory Group Meeting

Representative Group	Invitee	Attendee	Affiliation
Carriers			
Highway	Jeffrey Cooney	Yes	Tri-State Motor Transit Co.
Rail	Leo Tierney	Yes	Union Pacific Railroad
Water	Craig Philip	No	Ingram Barge Co.
Shippers	John Vincent	Yes	GPU Nuclear
	Julie Jordan	No	Edison Electric Institute
	Michael Kirkland	Yes	General Electric
State/Local Government	Alan Turner	Yes	Colorado State Highway Patrol
	Rose Hammitt	Yes	Illinois Department of Nuclear Safety
	Rick Bamsey	Yes	Iowa Emergency Management Division
	Robert Halstead	Yes	Nevada Nuclear Waste Project Office
	James Reed	No	National Conference of State Legislatures
Regional State	James Miernyk	Yes	Western Interstate Energy Board
Tribal Government	Mervin Tano	No	Council of Energy Resource Tribes
Public Interest Group	Robert Tipple	Yes	National Safety Council
	Ted Glickman	No	Resources for the Future
Nuclear Waste Technical Review Board	Sherwood Chu	Yes	Nuclear Waste Technical Review Board
Nuclear Regulatory Commission	John Cook	No	Nuclear Regulatory Commission
U.S. Department of Energy	Michael Conroy	Yes	Transportation Management Division
	Susan Smith	No	Office of Civilian Radioactive Waste Management
U.S. Department of Transportation	Joseph Nalevanko	Yes	Research and Special Programs Administration
	Claire Orth	Yes	Federal Railroad Administration
	E.P. Pfersich	No	U.S. Coast Guard
	Henry Sandhusen	Yes	Federal Highway Administration
	Robert Walter	Yes	Volpe National Transportation Systems Center
	Paul Zebe	Yes	Volpe National Transportation Systems Center
	Gary Watros	Yes	Volpe National Transportation Systems Center
Contractor Support	John Allen	Yes	Battelle
	David Kerr	Yes	Battelle
	Mark Abkowitz	Yes	Abkowitz and Associates, Inc. (AAI)
	Phani Raj	Yes	Technology and Management Systems, Inc. (TMS)
	Kitty Hancock	Yes	Abkowitz and Associates, Inc. (AAI)
	Emily Goodenough	Yes	Abkowitz and Associates, Inc. (AAI)

Appendix C

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Appendix C. Bibliography

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Appendix D

HazTrans Model Description

Appendix D. HazTrans Model Description*

Model Overview

This appendix provides a brief description of the current version and project use of HazTrans, a risk management product of Abkowitz and Associates, Inc. (AAI), of Nashville, Tennessee. HazTrans, used in this study to perform transportation route risk assessments, is a geographic information systems (GIS)-based application, which uses longitude and latitude coordinates to combine data that otherwise would be difficult or impossible to integrate.

HazTrans utilizes computerized highway, rail, and waterway transportation networks, derived from Federal data maintained at Oak Ridge National Laboratory in Oak Ridge, Tennessee. The highway network contains all Interstate, U.S., and State highways, as well as some major local arterials. The rail network includes both mainline and branch track and contains information on railroad operating rights. The waterway network contains all navigable intracoastal and intercoastal waterways (including the Panama Canal), and includes the representation of all locks and dams.

AAI has augmented the network databases with additional attributes, such as travel time, accident likelihood, and neighboring population. These attributes have been formed using a variety of transportation and demographic information sources and the results of scientifically credible transportation research studies. For example, population statistics are calculated using the 1990 Census by overlaying the block-level data onto the transportation networks and counting the population that resides within proximity of each segment and transfer point. Similarly, highway truck accident statistics are derived from a recent Federal Highway Administration study focusing on truck transport of hazardous materials.

Routing Criteria

To perform a routing analysis in HazTrans, the user must specify the mode, the origin and destination, the criteria to be used to determine the route, and any restrictions that should be placed on the route. These features were used in the study to select candidate routes to include in the case study sample.

The criteria used to select a route can be based on a single or weighted combination of economic and safety measures. Selecting travel time, for example, as the sole criterion will result in the quickest route from the origin to the destination. Safety measures include release-causing accident likelihood (i.e., the likelihood that there will be an accident that will result in a release at some point along the route), population exposure along the route, and a composite risk measure. Designated routes can also be represented and evaluated in HazTrans using special function commands.

* HazTrans is a registered trademark of Abkowitz & Associates, Inc., Nashville, Tennessee.

In addition to using differing criteria and weights to select and evaluate candidate routes, HazTrans provides the capability to specify various types of route restrictions. These restrictions fall into four categories: (1) specific nodes or links, (2) area-wide impacts, (3) link groups based on segment attributes, and (4) the location of mode-specific activities.

HazTrans output provides both segment and route-level statistics. These statistics can be used to supply input data to other risk models (e.g., population, travel times, stop locations, etc. as inputs to Radtran 4) or to support HazTrans risk screening models directly.

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Appendix E

Radtran 4 Model Description

Appendix E. Radtran 4 Model Description

Model Overview

Radtran 4 is a sophisticated computer program developed to evaluate radiological consequences of incident-free transportation, as well as the radiological risks caused by vehicular accidents occurring during transportation. Radtran 4 was developed (and is maintained) by Sandia National Laboratory (SNL) under contract to the U.S. Department of Energy. The following description of Radtran 4 has been compiled from source documents prepared over time by Radtran developers.

SNL developed the original Radtran code in 1977 in conjunction with preparation of NUREG-0170, "Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes." The analytical capabilities of the code were expanded and refined in subsequent versions. Radtran 4 contains advances in handling route-related data and in treating multiple-isotope materials.

The Radtran 4 code is designed to analyze the radiological impact of transporting radioactive material and combines meteorological, demographic, health physics, transportation, packaging, and material factors to evaluate both incident-free and accident risks.

Evaluation Methodology

Any evaluation of impacts on the public from transporting radioactive material requires some means of assessing health effects. Radtran uses a model based on the U.S. Nuclear Regulatory Commission's 1975 report entitled *Calculation of Reactor Accident Consequences*, which evaluates early fatalities, early morbidities, genetic effects, and latent cancer fatalities.

Radionuclides being evaluated are first subdivided into two classes: (1) external penetrating radiation hazards and (2) internal radiation hazards. External sources irradiate the total body, whereas the consequences of exposure to internal sources are dependent on the specific organs irradiated. External exposure can occur as a result of direct exposure to a localized source, from exposure to contaminated surfaces (groundshine), or from penetrating radiation from a passing cloud (cloudshine). Direct exposure can occur in either incident-free or vehicular accident scenarios. Groundshine and cloudshine exposure only occur following accidents.

Despite requirements designed to minimize exposure, whenever radioactive material is transported, members of the general population are exposed to extremely small doses of external penetrating radiation from x-rays, gamma rays, or exposure neutrons. In Radtran 4, the general population is divided into eight population subgroups: (1) crew, (2) passengers, (3) cargo handlers, (4) flight attendants, (5) warehouse personnel, (6) people in the vicinity of the vehicle while it is stopped, (7) people surrounding the transport link on which the vehicle is moving, and (8) people sharing the transport link with the vehicle. Total doses (in person-rem) are computed for each of these subgroups.

Two factors are considered in evaluating the impact of accidents that involve vehicles carrying radioactive shipments: probability and consequence. The probability that an accident releasing radioactive material will occur is described in terms of the expected number of accidents of a given severity for each transport mode, together with the package response to such an accident. The consequence of an accident is expressed in terms of the potential effects of the release of a specified quantity of radioactive material to the environment or the increased direct exposure of persons to ionizing radiation resulting from damaged package shielding. Risk is defined as the product of probability and consequence.

Radtran 4 contains mathematical models of transportation environments; these models have been formulated to yield conservative estimates of integrated population dose in a way that can be supported by available data. These models neglect features of the transportation environment that either do not affect the calculated risk values or reduce conservatism (e.g., the width of the median on divided highways).

Wherever possible, Radtran 4 combines calculational simplicity with general conservatism. For example, all routes by all modes are modeled as linear and flat without grade or curves. In addition to ease of calculation for the integrated incident-free off-link and on-link doses for a moving source, this model also yields conservative estimates of these doses that are applicable to all routes by all modes. Similarly, all highway and rail links are treated as being one lane (or track) in width for the purpose of estimating distance to off-link population, but as being two lanes wide (one lane or track in each direction) for the purpose of estimating on-link doses. The first treatment is used to achieve symmetry (and, hence, mathematical simplicity) around the lane in which the shipment is located and is also slightly conservative. The second treatment (one lane in each direction) yields the smallest perpendicular distance to the traffic traveling in the opposite direction, which again is conservative. The latter treatment also implies that all rail routes are modeled as having double tracks, which is another small increment of conservatism for rail-mode calculations.

Radtran 4 is designed for evaluating specific routes on a link-by-link basis. This option allows the user to independently analyze up to 40 separate route segments for each computer analysis. On each segment, the user assigns values representing the following route-related parameters:

- Mode (numerical designator)
- Segment length (km)
- Vehicle velocity (km/hr)
- Population density (persons/km^2)
- One-way traffic count (vehicles/hr for all lanes)
- Accident rate (accidents/km)
- Character designation (rural, suburban, or urban)
- Link type (1 = freeway, 2 = non-freeway, or 3 = other modes).

The ability to include link-specific information provides the capability to compare risks between routes and modes necessary for evaluating the significance of route factors and for comparing radiological risks among routing alternatives.

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Appendix F

Derivation of Transport Radiation Risk Models

Appendix F. Derivation of Transport Radiation Risk Models

Background

The development of fundamental relationships for measuring radiation exposure was described in Chapter 5 of this report. In this appendix, derivations of the model formulations are presented in more detail.

Scope of the Models

Radiation risk is composed of exposure to the following population groups:

- **Off-Link Population**—people residing, working or otherwise congregating in areas within the zone of radiation influence from the route of spent nuclear fuel shipment
- **On-Link Population**—passengers in other vehicles encountered along the route
- **Crew**—personnel within the immediate vicinity of the cask (e.g., primary crew, onboard security personnel, inspectors)
- **Population at Stops**—transportation workers away from the immediate vicinity of the cask (and emergency responders in the case of accidents) and general population nearby
- **Handling Personnel**—workers at an intermodal transfer terminal.

The risk evaluation models described in this appendix include considerations of the following types of risks:

- Incident-free radiological exposure
- Radiological exposure as a result of accidental release of nuclear materials into the environment.

Model Description

Assumptions

In the models presented below, the following assumptions are made:

- The models are applicable to a single mode only; coefficient values are applicable to each specific mode.
- The width of radiation effect zones for each mode is a constant.

- An individual shipment contains a single cask; multiple cask shipments are *not* considered.
- Risks to handlers arise only at intermodal transfer facilities.

Model symbols are defined in the nomenclature appearing at the end of this appendix.

Incident-Free Exposure Model

Consider the shipment of a single cask from an origin, O, to destination, D, as shown schematically in Figure F-1. The total risk from a single shipment is

$$R_{IFE} = R_1 + R_2 + R_3 + R_4 + R_5 \tag{F-1}$$

where:

R_{IFE} =total risk from incident free exposure (person-rem)
R_1 =risk to off link population
R_2 =risk to on link population
R_3 =risk to crew
R_4 =risk to population at stops
R_5 =risk to handlers

Each component risk is modeled below, consistent with fundamental physical considerations.

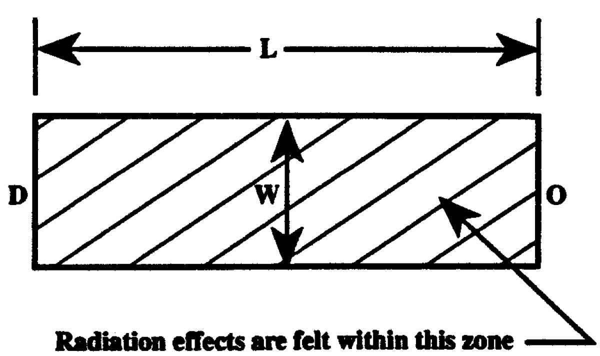

Figure F-1. Schematic representation of a shipment route attributes.

Off-Link Population Exposure. The risk to off-link population is given by

$$R_1 = \left[\begin{array}{c}\text{number of persons} \\ \text{exposed over the route}\end{array} \times \begin{array}{c}\text{average duration of} \\ \text{exposure of each individual}\end{array} \right] \qquad \text{(F-2)}$$

with

$$\text{the number of people exposed} = pLW \qquad \text{(F-3)}$$

The premise of this model is that the duration of exposure to an off-link individual is inversely proportional to the speed of the vehicle:

$$\text{average duration of offlink individual exposure} = \frac{a_1'}{U_v} \qquad \text{(F-4)}$$

where a_1' is a constant.

Note, also that

$$L = U_v \, t_L \qquad \text{(F-5)}$$

Hence

$$R_1 = a_1 \times \frac{pLW}{L} \, t_L \qquad \text{(F-6)}$$

or

$$R_1 = a_1 \, p \, t_L \qquad \text{(F-7)}$$

In this formulation, a_1, which combines a_1* and W (assumed constant), is also a constant. Therefore, the off-link risk is dependent only on the average population density and the duration of shipment.

On-Link Population Exposure. Figure F-2* represents a schematic of the on-link traffic situation (the highway mode is represented; however the same schematic is assumed to be applicable to the other modes).

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* In Figure F-2, subscript 1 represents the traffic moving in the same direction as the spent nuclear fuel shipment and subscript 2, the traffic moving in the opposite direction.

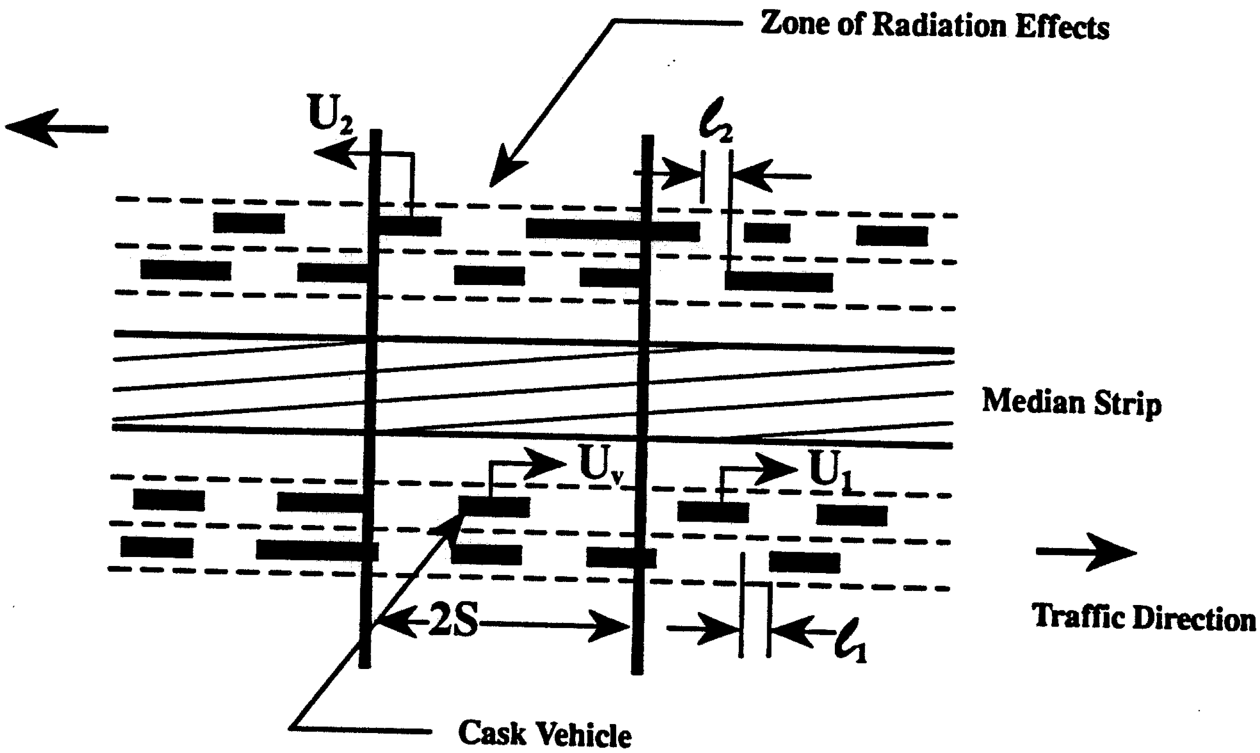

Figure F-2. Schematic representation of the on-link traffic vehicles being exposed to the effects of radiation from a moving spent nuclear fuel shipment.

The radiation exposure risk is given by the equation:

$$R_2 = \begin{bmatrix} \text{number of} \\ \text{persons} \\ \text{per vehicle} \end{bmatrix} \times \begin{bmatrix} \text{number of on-link} \\ \text{vehicles exposed} \\ \text{during the time } t_L \end{bmatrix} \times \begin{bmatrix} \text{average duration} \\ \text{of exposure of} \\ \text{each vehicle} \end{bmatrix} \qquad \text{(F-8)}$$

The initial development is for traffic moving in the same direction as the shipment. The results are then generalized and applied to traffic moving in the opposite direction.

Taking into consideration traffic in all lanes moving the same direction as the shipment, the mean separation distance between vehicles is

$$\ell_1 = U_1 \, t_T \qquad \text{(F-9)}$$

and

$$T_1 = 1/t_T \qquad \text{(F-10)}$$

The relative velocity of "same-direction" vehicles with respect to the cask vehicle is

$$U_r = U_1 - U_v \tag{F-11}$$

If the time duration for another vehicle to pass the cask vehicle is t_r, then

$$t_r = \frac{\ell_1}{U_1 - U_v} \tag{F-12}$$

Hence, in a time duration t_r the total number of vehicles N_v that will pass the cask vehicle is

$$N_v = \frac{t_L}{t_r} \tag{F-13}$$

Substituting the prior equations and simplifying:

$$N_v = \frac{(U_1 - U_v)}{U_1} T_1 \; t_L \tag{F-14}$$

Each on-link vehicle is assumed to be exposed to radiation when it is within $\pm$ S/2 longitudinal distance of the cask vehicle. Hence the duration of exposure for each vehicle becomes

$$t_e = \frac{2S}{(U_1 - U_v)} \tag{F-15}$$

where 2S represents the total length (parallel to the direction of motion of the spent nuclear fuel shipment) over which the radiation effects are significant.

Combining the previous equations, the on-link, same direction travel exposure risk becomes

$$\left[R_2\right]_{\text{SAME DIRECTION}} = a'_{2,1} \; N_p \; T_1 \; t_L / U_1 \tag{F-16}$$

where $a'_{2,1}$ is a constant of proportionality. If the on-link vehicle speed (U_1) is assumed to be a fixed ratio to the cask vehicle speed and the number of passengers per vehicle is constant, then the above equation becomes

$$\left[R_2\right]_{\text{SAME DIRECTION}} = a_{2,1} \; T_1 \; t_L^2 / L \tag{F-17}$$

From this, the risk is *not* dependent on the relative speed between the traffic and cask vehicle. Therefore, whether a vehicle is moving with the cask vehicle or in the opposite direction, the form of equation is the same and the exposure risk to traffic in the opposite direction will be

$$[R_2]_{\text{OPPOSITE DIRECTION}} = a'_{2,2}\ N_p\ T_2\ t_L/U_2 \tag{F-18}$$

or

$$[R_2]_{\text{OPPOSITE DIRECTION}} = a_{2,2}\ T_2\ t_L^2/L \tag{F-19}$$

Equations 17 and 19 can be combined to a single equation of the type

$$[R_2]_{\text{ON-LINK}} = a_2\ T\ t_L^2/L \tag{F-20}$$

where T is the mean traffic density (vehicles/hour) on the route. The definition of T involves all lanes in the route segment; that is, the mean of the vehicle density crossing a point per hour in each direction.

Evaluation of Traffic Density for Multi-Lane Routes. The traffic density value to be used in equations 17, 19, and 20 is calculated as follows.

Let

$T_{1,i}$ = Traffic count in direction 1, traffic lane i

y_i = Distance of lane i from the lane in which the spent nuclear fuel shipment is moving (this is the distance measured normal to the direction of motion of the spent nuclear fuel shipment).

Case 1: Radiation Zone is Rectangular. The radiation zone is assumed to be rectangular along a transport distance of 2S and extends W distance on either side of the cask vehicle. In addition, all lanes of traffic on either side of the cask vehicle are assumed to be within a distance W. Under these assumptions

$$T_1 = \sum_{i=1}^{m} T_{1,i} \tag{F-21}$$

and

$$T_2 = \sum_{i=1}^{n} T_{2,i} \tag{F-22}$$

where m and n represent, respectively, the total number of traffic lanes in directions 1 and 2.

The total traffic density, T , used in equation 20, is then

$$T = T_1 + T_2 \tag{F-23}$$

Case 2: Radiation Zone is Circular. If the radiation zone surrounding the spent nuclear fuel shipment is assumed to be circular with radius S, and if all traffic lanes are intersected by this circle

$$T_1 = \sum_{i=1}^{m} \left[T_{1,i} \times \left(1 - \frac{y_i^2}{S^2}\right)^{½} \right] \tag{F-24}$$

and

$$T_2 = \sum_{i=1}^{n} \left[T_{2,i} \times \left(1 - \frac{y_i^2}{S^2}\right)^{½} \right] \tag{F-25}$$

The total traffic density T value is again given by equation 23.

On-Board Crew Exposure. Crew exposure is directly proportional to the average number of personnel and the duration of transit:

$$R_3 = a_3 \times \left[\begin{matrix} \text{number of} \\ \text{crew, inspectors} \end{matrix} \times \begin{matrix} \text{average duration of} \\ \text{exposure of each individual} \end{matrix} \right] \tag{F-26}$$

or

$$R_3 = a_3 \, N_{crew} \, t_L \tag{F-27}$$

Population Exposure at Stops. The population exposure risk at stops can be estimated by

$$R_4 = \left[\begin{matrix} \text{number of} \\ \text{stops over length L} \end{matrix} \times \begin{matrix} \text{average number of} \\ \text{persons exposed per stop} \end{matrix} \times \begin{matrix} \text{average duration} \\ \text{of exposure} \end{matrix} \right] \tag{F-28}$$

The number of stops may be assumed (without significant loss of generality) to be proportional to the total distance of travel, or

$$R_4 = a_4 \, L \tag{F-29}$$

where

a_4 =coefficient for stop risk
L =trip distance.

Risks to Intermodal Handling Personnel. The handling risk is assumed to occur only for intermodal transfers when the casks have to be handled by transportation personnel. Both the number of handlers and the average duration of handling are assumed to be constant. Hence, the risk itself is considered to be constant, irrespective of the distance of transportation:

$$R_5 = a_5 H_1 \tag{F-30}$$

where

a_5 = coefficient for handling exposure
H_1 = Boolean variable (i.e., equal to 1 for intermodal and 0 for all other modes).

Total Incident-Free Risk. Total incident-free risk is then expressed as

$$R = a_1 \, p \, t_L + a_2 \, T \, \frac{t_L^2}{L} + a_3 \, N_{crew} \, t_L + a_4 \, L + a_5 \, H_1 \tag{F-31}$$

The different coefficients are considered constants and are not dimensionally consistent. The product of the coefficients and their respective parameter groups, however, have units of radiation dosage expressed in person-rems.

Radiological Accident Risk Model

The radiation risk from accidental release is calculated as follows

$$R = \begin{matrix}\text{probability of an}\\ \text{accidental release}\end{matrix} \times \begin{matrix}\text{consequence of release}\\ \text{(in person-rem)}\end{matrix} \tag{F-32}$$

The probability of release per shipment on a route is expressed by

$$P_r = \begin{matrix}\text{probability}\\ \text{of release}\end{matrix} = \left[\begin{matrix}\text{mean accident rate per}\\ \text{unit length per vehicle}\end{matrix} \times L \times P(r \mid Acc)\right] \tag{F-33}$$

where

P_r = probability of release anywhere on the trip per shipment
$P(r \mid Acc)$ = conditional probability of release given that an accident has taken place
L = travel length

i.e.,

$$P_r = b_1 \, S_A \, L \, P(r|Acc) \tag{F-34}$$

The consequence calculation is somewhat more complicated. The potential dispersal of radioactive nuclei in the atmosphere and the associated area of hazard are schematically represented in Figure F-3. The relationship is

$$\text{consequence} = \frac{\text{number of people}}{\text{exposed to the cloud}} \times \frac{\text{average duration}}{\text{of exposure}} \tag{F-35}$$

or

$$C = b_2 \, p' \, A \times \frac{\sqrt{A}}{U_{wind}} \tag{F-36}$$

where p' = population density, including both general and occupational population.

In equation 35, a measure of the duration of exposure is the average time of transit of radionuclides carried by wind across the hazard area. This windward length is estimated to be directly proportional to the square root of hazard area.

Note also that in equation 35 the hazard area, A, is a function of the quantity of radioactive materials released into the environment. This quantity depends on both the vehicle payload and the severity of the accident. However, if all possible conditional probabilities of release of different quantities (i.e., accident severity) are combined, then the term A in equation 35 can be interpreted as the area corresponding to a mean quantity released and P(r|Acc) in equation 33 will then correspond to the conditional probability of release of this mean quantity.

Combining equations 33 and 35, and noting that (1) mean conditional release probability is independent of the route chosen, (2) mean quantity released is constant over a given mode (hence A is a constant over mode), and (3) wind and other atmospheric conditions are constant; the relationship becomes

$$R = b \, p \, S_A \, L \tag{F-37}$$

where b is the radiological accident coefficient.

Note that accident release risk has a direct relationship to mean population density, length of travel and mean accident rate. It does not depend on the duration of travel.

Nomenclature

a	Coefficients of various risk terms
A	Radiation dose hazard area (sq. km.)

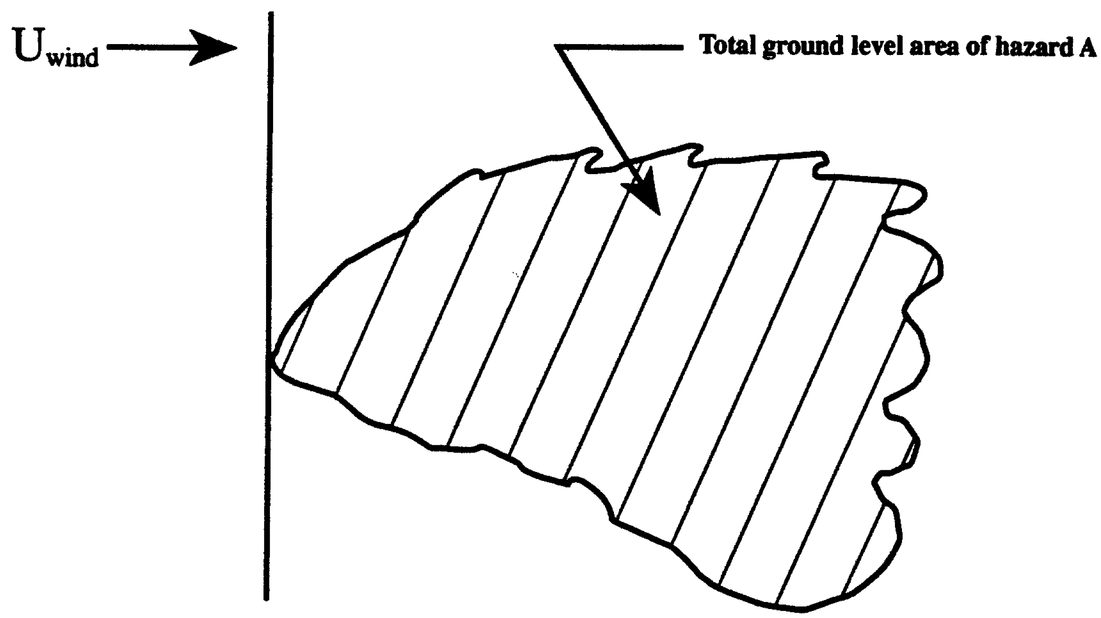

Figure F-3. Schematic of radioactive nuclide dispersion and hazard to off-link population.

b	Coefficients of various risk terms
C	Consequence of an accidental radiation release (person-rem)
H_1	Boolean with value 1 or 0
L	Total length of the trip (or route length) for the cask vehicle (km)
m	Number of traffic lanes in direction 1
n	Number of traffic lanes in direction 2
N_{crew}	Average number of crew per vehicle (personnel within 10 meters of the cask)
N_p	Average number of people per vehicle (assumed the same for both directions of traffic)
N_v	Total number of vehicles exposed to radiation effects during the transit of the cask vehicle (in time t_L)
P	Probability that in a shipment an accident occurs resulting in the release of radionuclides to the atmosphere

$P(r\|Acc)$	Conditional probability of release given that a traffic accident has occurred
R	Total radiation exposure risk per shipment (person-rem)
R_1	Non-accident exposure risk to off-link population (person-rem)
R_2	Non-accident exposure risk to on-link population (person-rem)
R_3	Crew exposure risk in non-accident transportation (person-rem)
R_4	Exposure risk at stops (person-rem)
R_5	Intermodal handling risk (person-rem)
S	Along link distance over which the radiation effects are important either in the front or at the back of spent nuclear fuel cask (km)
S_A	Mean accident rate over the entire length per shipment. It is also the probability of realizing an accident over a unit distance in a single shipment (#/km)
S_{AF}	Mean traffic fatal accident rate over the entire route
t_e	Mean duration of radiation exposure of each on-link vehicle (r)
t_L	Total duration of the trip for the cask vehicle (hr)
t_T	Mean time between vehicles crossing a specified point on the link (hr)
T	Mean traffic density on the mode over the duration of time that the cask vehicle is on the route (vehicles/hr)
U_v	Mean speed of cask vehicle = (L/t_L) (km/hr)
U_1	Mean speed of vehicles moving in the same direction of the cask vehicle (km/hr)
U_2	Mean speed of vehicles moving in the opposite direction of the cask vehicle (km/hr)
W	Total width of radiation effect zone along the route corridors (km)
y_i	Cross longitude distance to traffic lane i from the lane in which the SNF cask vehicle is moving (center to center distance between lanes)
ρ	Average density of population along the route lying entirely within semi-width W/2 on either side of the route (#/sq. km.)
ρ'	ρ based on consideration of both general and occupational population

$\ell 1$ Mean separation distance between vehicles moving in the same direction (km)

$\ell 2$ Mean separation distance between vehicles moving in the opposite direction (km)

Subscripts:

1 Traffic moving in the direction of the spent nuclear fuel cask vehicle

2 Traffic moving in the opposite direction

Appendix G

Development of Case Study Input and Output

Appendix G. Development of Case Study Input and Output

The purpose of this appendix is to provide a discussion of the information used to generate the case study inputs and outputs. The emphasis of this work was to support comparisons of safety impacts associated with different mode and route selections, which required several adjustments to the information provided to and received from the Radtran 4 analyses as described below (for more on Radtran 4, see Appendix E).

Primary Factors

The primary factors that provide the basis for the case studies include amount of material, emergency response, general population, occupational population, accident rate, trip length, and shipment duration. As outlined below, these factors were obtained from HazTrans, except as noted, for each of the 65 routes used in the case study analysis (for more on HazTrans, see Appendix D).

Amount of Material

Amount of material is quantifiable in the context of this analysis if it is handled as a post-processing activity once the relationship between primary factors and safety is established on a per-shipment basis. The relative payload capacity, as a modal selection factor, becomes a consideration when the number of shipments is compared. To extend the interpretation of case study results to consider amount of material, the cask payloads used in this analysis were two pressurized water reactor (PWR) assemblies per truck and fourteen PWR assemblies per rail and barge shipment. One common way to establish equivalency is to assume linearity in the radiological impacts per shipment.

Emergency Response

DOE has developed regional emergency management field offices that can assemble and dispatch qualified response teams to incidents involving nuclear material. The following ten regional field offices were identified and located:

Albuquerque, NM	Oak Ridge, TN
Argonne, IL	Richland, WA
Cincinnati, OH	Oakland, CA
Idaho Falls, ID	Aiken, SC
Las Vegas, NV	Brookhaven, PA

Each office determines the appropriate response and the best method for transporting the response unit to the incident site. For this reason, actual response times are very difficult to predict.

As a surrogate measure, emergency response time was represented as the average of the direct distance from the nearest field office to each route segment for that route. Distance was calculated using curvilinear distance from the nearest field office to the ends of each route segment using latitude and longitude coordinates. The segment response distance was taken as the average of the response distances to each end of the segment. A weighted average of response distances by segment length was then calculated to derive an overall route response measure.

Inherent in the use of "as-the-crow-flies" distances is the possibility of misrepresenting driving distance, available access to rail and water modes, or the possibility that teams may fly to the incident site. Because the intended purpose in the case study was to establish a surrogate measure of the proximity of qualified response to different locations along prospective routes, it was felt that the methodology could achieve this purpose given these limitations.

General Population

Exposure to residential population along transport routes was determined using HazTrans. HazTrans contains detailed 1990 Census residential population data by geographic location. This database was overlaid onto each case study route segment using common map referencing (latitude-longitude coordinates). The population within a ½-mile band around the segment was counted for the purpose of establishing the population density of interest. Population densities on route segments with fewer than 6 persons/km^2 were defined as rural; greater than 6 and fewer than 719 persons/km^2 were classified as suburban; locations over 719 persons/km^2 were defined as urban. This grouping was formed to accommodate Radtran 4 default input requirements.

The traffic sharing each route was based on assumptions made in previous radiological transport studies and in consultation with shippers and carriers. Highway traffic densities were based on assuming partially congested use of each roadway and the roadway capacity according to its functional classification. The traffic density for rail was assumed to be 2 trains/hr on mainline tracks and 0.2 trains/hr on all other lines. Traffic density on rivers and the intercoastal waterway was assumed to be one barge consist per hour; no traffic within significant exposure range was assumed for Great Lakes and off-shore locations.

Occupational Population

Occupational population was assumed to consist of on-board personnel (primarily crew and escorts) and inspectors at stops. The size of each group for each mode was obtained from telephone conversations with shippers and carriers directly involved in the movement of spent nuclear fuel. At the time of the Radtran 4 analyses, barge shipments of spent nuclear fuel had yet to occur. Discussions with a barge company and a shipper considering the use of barge transport, however, established the number of crew members for possible barge shipments.

Accident Rate

Accident rates for each mode and route combination were generated using the HazTrans system. HazTrans groups specific links into segment types based on their functional characteristics, and then assigns hazardous materials vehicle accident rates for each segment type based on previous scientific studies. Although the accident rates are reported on a per mile basis, they were subsequently converted to a per kilometer measure to accommodate Radtran 4 input requirements.

Accident rates utilized in the study are provided below:

Highway	
rural two-lane	2.19×10^{-6} per veh/mile
rural multilane undivided	4.49×10^{-6} per veh/mile
rural multilane divided	2.15×10^{-6} per veh/mile
rural freeway	0.64×10^{-6} per veh/mile
urban two-lane	8.66×10^{-6} per veh/mile
urban multilane undivided	13.92×10^{-6} per veh/mile
urban multilane divided	12.47×10^{-6} per veh/mile
urban one-way street	9.70×10^{-6} per veh/mile
urban freeway	2.18×10^{-6} per veh/mile
Rail	
mainline track	6.0×10^{-7} per car-mile
yards	2.04×10^{-5} per car-visit
sidings	2.40×10^{-6} per car-visit
Waterway	
coast	1.0×10^{-5} per veh/mile
MS/OH/TN/MO river systems	1.5×10^{-5} per veh/mile
open seas, Great Lakes	0.005×10^{-5} per veh/mile

Trip Length and Shipment Duration

Trip lengths were derived directly from HazTrans by summing the segment distances comprising each route. Shipment duration took into consideration varying operating speeds associated with each segment type, subject to mode-specific adjustments associated with stops and delays. Stop time and delay assumptions are discussed in the following sections.

Radtran 4 Input

Radtran 4 requires a substantial amount of information to perform a single analysis. Table G-1 lists all of the variables used by Radtran 4 along with their corresponding descriptions. The variables can be divided into modeling, material, mode and route variables. Modeling variables define the type of analyses to be performed and specify the amount and type of output to be provided by Radtran 4. Material variables determine the type of material being shipped and its properties. Mode variables specify the amount of material being shipped, the type of handling and shipment characteristics, and the severity and release information for possible accidents. Route variables specify the length, vehicle speed, population density, number and length of stops, traffic density and type of transportation link. Table G-1 includes a letter after each variable name to designate the type of variable as follows: modeling (D), material (T), mode (M) and route (R) variables.

Table G-1. Summary of Radtran 4 variable descriptions.

TITLE D		Alphanumeric title
FORM D		UNIT indicates population dose calculation
DIMEN		
	NISO D	Number of isotopes
	NSEV D	Number of accident-severity categories
	NGROUP D	Number of physical-chemical groups
	NRAD D	Number of radial areas used for nondispersal accident analysis
	NAREAS D	Number of areas used in dispersion accident analysis
PARM		
	IRNKC D	Flag for placing data on file 6 (Default = 1)
	IANA D	Analysis flag (Default = 3: both accident and incident-free)
	IUOPT D	Shielding options flag (Default = 2: persons in bldgs exposed at reduced level)
	ISEN D	Printing flag (1: incident-free and accident output tables)
	IPSQSB D	Dispersal accident flag (Default = 0: user-supplied time-integrated concentrations)
POPDEN R		Rural, suburban, and urban population densities (Default = 6, 719, 3861 people/km^2)
PACKAGE		
	LABGRP(J) T	Alphanumeric identifiers for physical-chemical groups
	PKGSZ1 T	First package-size threshold (Default = 0.5 m)
	PKGSZ2 T	Second package-size threshold (Default = 1.0 m)
SHIPMENT		
	LABISO(I) T	Alphanumeric isotope designators
NORMAL		
	NMODE M	Mode number (1 = truck, 2 = rail, 3 = barge)
	FTZNR R	Fraction of travel in rural zone
	FTZNS R	Fraction of travel in suburban zone
	FTZNU R	Fraction of travel in urban zone
	VELR R	Velocity in rural zone (km/hr)
	VELS R	Velocity in suburban zone (km/hr)
	VELU R	Velocity in urban zone (km/hr)
	CREWNO M	Number of crew on a shipment
	ADSTCW M	Average distance from radiation source to crew during shipment (m)
	HANDNO M	Number of handlings per shipment
	STOPTIM R	Stop time for shipment (hr)
	MINST R	Minimum stop time per trip for shipment (hr)
	TIMZR R	Distance-independent stop time per trip (hr)
	FMINCL R	Minimum number of rail inspections or classifications; rail mode only
	PDSTM	Number of persons exposed during stops
	RST M	Average exposure distance when stopped
	DISTOR M	Storage time per shipment (hr)
	PDSTOR M	Number of persons exposed during storage for shipment
	RSTOR M	Average exposure distance during storage (m)
	PPV M	Number of persons per vehicle sharing the transport link
	FRSHR R	Fraction of urban travel during rush hour
	FCTST R	Fraction of urban travel on city streets
	FTLFWY R	Fraction of rural and suburban travel on freeways by mode
	TCNTPR R	One-way traffic count in rural zones (veh/hr)
	TCNTPS R	One-way traffic count in suburban zones (veh/hr)
	TCNTPU R	One-way traffic count in urban zones (veh/hr)
	RPD M	Ratio of pedestrian density to urban residential population density (Default = 6)

Table G-1. Summary of Radtran 4 variable descriptions (continued).

	RR T	Building shielding factor for rural zones (Default = 1.0)
	RS T	Building shielding factor for suburban zones (Default = 0.87)
	RU T	Building shielding factor for urban zones (Default = 0.018)
	FNOATT M	Number of flight attendants for commercial passenger-air mode
TRANSFER		
	GAMMA T	Coefficients defining gamma component of radiation dose
	NEUTRON T	Coefficients defining neutron component of radiation dose
ACCIDENT		
	ARATMZ R	Accident rates (accidents/km)
	SEVFRC M	Fraction of accidents for each specified accident severity
MATERIAL		
	RPCVAL T	Factors that determine dose to 8 organs per unit of radioactivity of isotope inhaled
	INGVAL T	Factors that determine dose to 8 organs per unit of radioactivity of isotope ingested
DEFINE		
	ISONAM(k) T	Name of isotope
	ACCDNT(i,k) T	Isotope specific data
RELEASE		
	RFRAC M	Fraction of each physical-chemical group released in accident of each severity
	AERSOL M	Fraction of isotope of each dispersion category that is released in aerosol form
	RESP M	Fraction of aerosolized isotope of each dispersion category that is respirable
	AREADA D	Area of each isodose area (Defaults in Radtran 4 Users Manual) (m^2)
	DFLEV D	Time-integrated concentration of radionuclide in aerosol in each isodose area (Defaults in Radtran 4 Users Manual)
	PSPROB D	Probability of occurrence of each of six Pasquill atmospheric stability categories (Only required if IPSQSB = 1)
OTHER		
	RADIST M	Radii that define the exposure annuli used in nondispersal accident model (m)
	BDF M	Building dose factor
	XFARM R	Fraction of rural land under cultivation
	CULVL M	Cleanup level following an accident ($\mu Ci/m^2$)
	BRATE D	Breathing rate (m^3/s)
	ITRAIN M	For rail: 1 = general freight, 2 = dedicated rail
ECONOMIC		*not used for this evaluation*
ISOTOPES		
	NM M	Mode (same as NMODE)
	TABSPY(NM) M	Number of shipments
	PKGSHP(NM,m) M	Number of packages per shipment
	TIPKG(NM,m) T	Package dose rate at 1 m (mrem/hr)
	FRGAMA(m) T	Fraction of effective dose rate that is gamma radiation
	FRNEUT(m) T	Fraction of effective dose rate that is neutron radiation
	LABMAT(m) T	Material label
	LIBSAV(i) T	Name of isotope; must be equivalent to name in LABISO array
	CIPKG(i) M	Isotope-specific curies per package for isotope
	IPCGRP(i) T	Isotope-specific physical-chemical group for isotope; must be identical to LABGRP
	IDISP(i) T	Isotope-specific dispersability category for isotope
	PKGSIZ(m) M	Characteristic package dimension for material (m)
	DISTKM(NM) R	Distance (km)

Table G-1. Summary of Radtran 4 variable descriptions (continued).

LINK		
	LMODE(j) R	Mode (same as NMODE)
	LDIST(j) R	Length of link (km)
	LSPED(j) R	Speed of vehicle on link (km/hr)
	LPOPD(j) R	Population density along link (persons/km^2)
	LVDEN(j) R	One-way vehicle density on link (veh/hr)
	LARAT(j) R	Accident rate on link (accidents/km)
	LZONE(j) R	Zone type designator for link (R = rural, S = suburban, U = urban)
	LTYPE(j) R	Link type designator (1 = freeway, 2 = non-freeway, 3 = all other)

Legend:
D - modeling variables
T - material variables
M - mode variables
R - route variables

Modeling Assumptions

Modeling variables remained constant for all cases. Modeling assumptions included

- Conduct of both incident-free and accident analyses
- Use of eighteen user-supplied time-integrated concentration isopleths and areas representing air dispersion as developed by SNL in their data set [4,1,3], available for public use via remote telephone access
- Modeling of freight movements as exclusive-use shipments.

Material Assumptions

Material variables remained constant for all cases. Material assumptions included

- Spent nuclear fuel discharged from the reactor 5 years before transport
- Effective dose rate or transport index (TI) of fuel of 13 millirem/hr, the highest value permitted in Radtran 4*

* The TI is a regulatory quantity defined in the regulations of the International Atomic Energy Agency, the U.S. Department of Transportation, and the Nuclear Regulatory Commission as the maximum radiation level in millirem/hr at 2 meters from the vertical planes projected by the outer lateral surface of the vehicle for exclusive use shipments.

- Material that was modeled consisted of 15 major isotopes (Note: the isotopes listed do not represent the entire inventory present in spent nuclear fuel):

Cobalt-60	Cesium-137	Plutonium-240
Krypton-85	Cerium-144	Plutonium-241
Strontium-90	Europium-154	Americium-241
Ruthenium-106	Plutonium-238	Americium-243
Cesium-134	Plutonium-239	Curium-244

Mode Assumptions

As necessary, the mode variables were changed between highway, rail, and waterway transport. Where the mode variables also reflected material characteristics, such as CIPKG (isotope-specific curies per package), rail and waterway values were kept the same because the waterway analyses assumed the use of a rail cask. Mode assumptions included

- Existing type and size casks used for both highway and rail shipments
- Highway cask payload of 2 PWR assemblies; rail cask payload of 14 PWR assemblies (This provides a 1 to 7 ratio between highway and rail cask carrying capacity.)
- Number of casks per shipment and the number of shipments per mode set to one each for all modes
- Accident severities assumed to be different for each mode. Highway and rail severities were derived from work performed by Lawrence Livermore National Laboratory for the NRC; barge accident severities were adjusted from the rail severity distribution by reducing the five higher severity fractions by a factor of five and increasing the lowest severity accordingly (based on conversations with DOT contractor).
- Normal modal variables defining incident-free exposure determined for each mode based on discussions with shippers and carriers; kept constant for all analyses within each mode.

Route Assumptions

Route variables were changed as necessary between routes and included all of the arrays listed under LINK as well as the NORMAL variables relating to length and number of stops and rail inter-changes/inspections. The XFARM value was not included in the analyses because the ingestion risk under the accident risk results has been disabled within Radtran 4 by SNL. Note that all other variables indicated as route variables are overridden by the LINK information.

The stops and stop times used for each analysis varied by mode and route. For highway routes, the assumption was that one inspection occurred at each state line. This was reflected in the FMINCL variable. The Radtran 4 default value of 0.011 hr/km was used to represent other stop times for this mode. The stop relationships for both dedicated and manifest rail were obtained from discussions with DOT staff. The independent stop time (TIMZR) was incorporated into the dependent stop time (STOPTIM) and was calculated as follows:

Dedicated: (2 hrs + 8 hrs /classification & inspection) / total route length
Manifest: (16 hrs + 16 hrs/classification & inspection) / total route length

The resulting values were added into the dependent stop times, which were

Dedicated: 0.0055 hrs/mi for west of the Mississippi River and 0.0073 for east of the Mississippi River
Manifest 0.035 hrs/mi for west of the Mississippi River and 0.047 for east of the Mississippi River

An inspection was also included if the route went more than 1,000 miles without the occurrence of a classification. The stop time for waterborne shipments was calculated as follows:

Water: (1.5 hrs/lock & dam) / total route length.

Table G-2 presents the specific variables used for each mode or the source used to obtain those variables. In many cases, particularly for the material variables, the variable listed in the table represents an array of values for different properties or modal criteria. Standard data sets were used for these arrays as referenced in Table G-2.

Radtran 4 Output

The output from a Radtran 4 analysis as designed for this study includes incident-free and radiological accident risk values calculated in terms of person-rems. The five components of incident-free exposure include (1) crew risk, (2) handler risk (for intermodal only), (3) off-link (or surrounding) population risk, (4) on-link (or shared facility user risk), and (5) stop risk (people exposed during stops). The four components of radiological accident exposure include: (1) groundshine (from external exposure to deposited particles), (2) inhalation (from breathing in particles), (3) resuspension (from inhalation of particles deposited and then resuspended), and (4) cloudshine (from external exposure to passing cloud).

As indicated previously, shipments were assumed to travel via exclusive-use vehicles requiring no storage during transit. This assumption eliminates the calculated risks to passengers (exclusive of crew and escorts) and storage personnel. Also, because the ingestion risk calculations have been disabled by SNL within the current version of Radtran 4, the associated risk could not be obtained. This risk is much smaller than the other risks and so would not affect the magnitude of the overall radiological accident risk.

The current version of Radtran 4 limits route-specific analyses to 40 links. Very few of the routes analyzed in this case study contained fewer than 40 links. Therefore, each route was divided into sets of 40 links and the results from each set were added to compile the final risk values. Adjustments were made in cases where exposure was shipment (and not segment) based so as not to double-count their effects.

Table G-2. Summary of Radtran 4 input used for case analyses.

TITLE	highway	man.rail	ded.rail	water	intermodal
FORM	UNIT	UNIT	UNIT	UNIT	UNIT
DIMEN					
NISO	15	15	15	15	15
NSEV	6	6	6	6	6
NGROUP	5	5	5	5	5
NRAD	10	10	10	10	10
NAREAS	18	18	18	18	18
PARM					
IRNKC*	1	1	1	1	1
IANA*	3	3	3	3	3
IUOPT*	2	2	2	2	2
ISEN	1	1	1	1	1
IPSQSB*	0	0	0	0	0
POPDEN	*not used (in LINK)*				Suburban: 719*
PACKAGE					
LABGRP(J)	from Transnet TTC developed data set [4,1,3]: same for all modes				
PKGSZ1**	0.5	0.5	0.5	0.5	0.5
PKGSZ2**	1.0	1.0	1.0	1.0	1.0
SHIPMENT					
LABISO(I)	from Transnet TTC developed data set [4,1,3]: same for all modes				
NORMAL					
NMODE	1	2	2	3	2
FTZNR	*not used (in LINK)*				0
FTZNS	*not used (in LINK)*				1
FTZNU	*not used (in LINK)*				0
VELR	*not used (in LINK)*				0
VELS	*not used (in LINK)*				1
VELU	*not used (in LINK)*				0
CREWNO†	2 #	2 #	5 #	10 #	0
ADSTCW	3.1 *#	100 #	100 #	60 #	0
HANDNO	0	0	0	0	1
STOPTIM	0.011 *#	varies w/ route	varies w/ route	varies w/ route	0
MINST	0	0	0	0	0
TIMZR	0	0	0	0	12 #
FMINCL	varies w/ route	2	2	0	1
PDST	50 #	*not used*	*not used*	10 #	*not used*
RST	50 #	*not used*	*not used*	50 #	*not used*
DTSTOR	*not used (assumed no storage)*				
PDSTOR	*not used (assumed no storage)*				
RSTOR	*not used (assumed no storage)*				
PPV	1.2	3 #	3 #	#	0
FRSHR	*not used (in LINK)*				
FCTST	.05	1.0	1.0	0	0
FTLFWY	.85	0	0	0	0
TCNTPR	*not used (in LINK)*				0
TCNTPS	*not used (in LINK)*				1
TCNTPU	*not used (in LINK)*				0
RPD**	6.0	6.0	6.0	6.0	0
RR**	1	1	1	1	1
RS**	.87	.87	.87	.87	1
RU**	.018	.018	.018	.018	1
FNOATT	*not used (air mode not used)*				

Table G-2. Summary of Radtran 4 input used for case analyses (continued).

TRANSFER						
	GAMMA**	as defined on p. 4-8 of Radtran 4 manual: same for all modes				
	NEUTRON**	as defined on p. 4-8 of Radtran 4 manual: same for all modes				
ACCIDENT						
	ARATMZ	*not used (in LINK)*				
	SEVFRC	from Modal Study: see section of table labeled ACCIDENT SEVERITY. . .				
MATERIAL						
	RPCVAL**	as defined in Radtran 4 data base: same for all modes				
	INGVAL**	as defined in Radtran 4 data base: same for all modes				
DEFINE						
	ISONAM(k)	*not used (no new isotopes used for these analyses)*				
	ACCDNT(i,k)	*not used (no new isotopes used for these analyses)*				
RELEASE						
	RFRAC	from Transnet TTC developed data set [4,1,3]: same for all modes				
	AERSOL	from Transnet TTC developed data set [4,1,3]: same for all modes				
	RESP	from Transnet TTC developed data set [4,1,3]: same for all modes				
	AREADA**	as defined by Radtran 4: same for all modes				
	DFLEV**	as defined by Radtran 4: same for all modes				
	PSPROB	*not used (national averages used for user defined dispersion)*				
OTHER						
	RADIST	*not used (dispersion model used for HLW and NSF)*				
	BDF**	8.6E-3	8.6E-3	8.6E-3	8.6E-3	8.6E-3
	XFARM**	0.5	0.5	0.5	0.5	0.5
	CULVL**	0.2	0.2	0.2	0.2	0.2
	BRATE**	3.3E-4	3.3E-4	3.3E-4	3.3E-4	3.3E-4
	ITRAIN	0	1	2	0	1 or 2
ECONOMIC		*not used for these evaluations*				
ISOTOPES						
	NM	-1	-2	-2	-3	-2
	TABSPY(NM)	1	1	1	1	1
	PKGSHP(NM,m)	1.0	1.0	1.0	1.0	1.0
	TIPKG(NM,m)	13.0	13.0	13.0	13.0	13.0
	FRGAMA(m)	1.0	1.0	1.0	1.0	1.0
	FRNEUT(m)	0.0	0.0	0.0	0.0	0.0
	LABMAT(m)	SFUEL	SFUEL	SFUEL	SFUEL	SFUEL
		See section of table labeled ISOTOPE ARRAYS for input values for the following 4 variable groups.				
	LIBSAV(i)	as in Transnet TTC developed data set [4,1,3]: same for all modes				
	CIPKG(i)	data set [4,1,3]	exa p. 5.28 Radtran 4	exa. p. 5.28	exa. p. 5.28	exa. p. 5.28
	IPCGRP(i)	as in Transnet TTC developed data set [4,1,3]: same for all modes				
	IDISP(i)	as in Transnet TTC developed data set [4,1,3]: same for all modes				
	PKGSIZ(m)	5.2	5.2	5.2	5.2	5.2
	DISTKM(NM)	*not used (in LINK)*				
LINK						
	LMODE(j)	1	2	2	3	*not used*
	LDIST(j)	from Haztrans				*not used*
	LSPED(j)	from Haztrans				*not used*
	LPOPD(j)	from Haztrans (1/2 mile band width ~ 800 m)				*not used*
	LVDEN(j)	from Haztrans				*not used*
	LARAT(j)	from Haztrans				*not used*
	LZONE(j)*	R, S, U based on LPOPD(j) > 6, 719, 3861 resp.				*not used*
	LTYPE(j)	1 or 2	3	3	3	*not used*

Table G-2. Summary of Radtran 4 input used for case analyses (continued).

Accident Severity Arrays for all Population Zones

Level	Highway (Mode)	Rail (Mode)	Water (Mode)
1	9.94E-01	9.94E-01	9.99E-01
2	4.05E-05	2.02E-03	8.10E-06
3	3.82E-03	2.72E-03	7.64E-04
4	1.80E-03	5.55E-04	3.60E-04
5	1.55E-05	6.14E-04	3.10E-06
6	9.84E-06	1.25E-04	1.97E-06

Fractional Release Arrays for Each Severity by IPCGRP

Group 1	Group 2	Group 3	Group 4	Group 5
0	0	0	0	0
0	0	0	0	0
1.20E-02	0	0	0	0
1.20E-02	1.00E-02	1.00E-08	1.00E-08	1.00E-08
1.20E-02	1.00E-01	2.00E-04	5.00E-08	1.00E-06
1.20E-02	1.10E-01	2.80E-04	5.00E-08	4.20E-05

Isotope Arrays

LIBSAV	CIPKG Highway	CIPKG Rail & Water	IPCGRP	IDISP
C060	9.22E+01	6.45E+02	PKG1	2
KR85	6.10E+03	4.27E+04	PKG2	3
SR90	5.96E+04	4.17E+05	PKG4	5
RU106	1.62E+04	1.14E+05	PKG5	5
CS134	2.74E+04	1.92E+05	PKG3	4
CS137	8.76E+04	6.13E+05	PKG3	4
CE144	1.22E+04	8.53E+04	PKG4	4
EU154	7.00E+03	4.90E+04	PKG4	4
PU238	2.96E+03	2.07E+04	PKG4	5
PU239	4.10E+02	2.87E+03	PKG4	5
PU240	4.68E+02	3.28E+03	PKG4	5
PU241	1.26E+05	8.85E+05	PKG4	5
AM241	1.29E+03	9.00E+03	PKG4	5
AM243	1.99E+01	1.39E+02	PKG4	5
CM244	1.79E+03	1.25E+04	PKG4	5

* Default values provided within Radtran 4 used.
** Value not explicitly included in input files but default values within Radtran 4 used.
† 5 crew members assumed on train; only 2 assumed within exposure to cask.
\# Values obtained from shippers and/or carriers.
*# Default values used by Radtran confirmed by shippers and/or carriers

Several "NORMAL" variables are hard-set within Radtran and cannot be changed. These variables are:

PPH - persons per handling
D_H - distance from handlers to source
T_H - exposure time for handlings
r_i - distance from inspector to source
T_i - exposure time for inspections
SF_{ST}- shielding factor at rail stops

Adjustments to Radtran 4 Results

Because of assumptions within Radtran 4, some modes do not include certain incident-free doses, and some doses are calculated differently. Table G-3 addresses the manner in which these differences were addressed for the Radtran 4 case study analyses. Table G-3 displays a matrix of the incident-free doses for the different modes being evaluated. The numbers within the matrix refer to descriptions provided following the matrix.

Table G-3. Adjustments to Radtran 4 results.

	Highway	Rail	Water
On-link: opposite direction	1	1	1
On-link: same direction	1	2	2
Off-link	1	1	1
Crew: on board	1	3	4
Crew: inspection	5	5	5
Stops	1	6	1

1. Indicates that the dose calculation performed within Radtran 4 was used directly.

2. Indicates that Radtran 4 does not currently calculate a dose for this mode and that this is realistic.

3. The crew on-board dose is currently only calculated for the highway mode. Analysis was performed using the rail mode input file with all mode flags changed from 2 to 1 (rail to tractor-trailer). The resulting crew on-board dose was added to the original rail inspection dose to obtain a final crew dose.

4. The crew on-board dose is currently calculated only for the highway mode. Analysis was performed using the barge input file with all mode flags changed from 3 to 1 (water to tractor-trailer). The resulting crew on-board dose was added to the original barge inspection dose to obtain a final crew dose.

5. The crew inspection dose is only calculated for the rail and water modes. Problems were identified within Radtran 4 for the rail inspection calculations. The number of inspections has two components, FMINCL (minimum number of inspections) and a constant times the length. FMINCL was included in every link. The modification was to calculate the risk directly, replacing the two terms with the actual number of inspections for each route. The resulting inspection crew dose was added to the on-board crew dose to obtain a final crew dose.

6. Radtran 4 results for the rail model stop-risk calculations were modified to account for the following two factors. First, a risk value was being printed only for suburban links. The formulation of the stop risk calculation uses the suburban population density for rail yards. Because of this, the code only checks for suburban links in calculating the risk. Instead, all links should be considered even if the suburban population density is used in place of link-specific density. When this was done using a spreadsheet and the link-specific information, the stop risk was much higher than the other incident-free risks.

   When the equation was re-evaluated, it appeared that the distance-independent stop-time was being summed over every link with the distance-dependent calculation. To account for this, the independent stop time was divided by the total length of the route and added to the dependent stop time during the input phase. The final rail stop risk calculations were performed in a spreadsheet independent of Radtran 4 by using a stop-risk value from the Radtran 4 analysis, dividing by the length and population density of the link and multiplying by the total length of the route and the suburban population density of 719 persons/km^2.

Non-Radiological Accident Risks

Since Radtran 4 does not model non-radiological transport risks, this measure was derived outside of the Radtran 4 methodology using HazTrans and national accident statistics. Non-radiological risk was measured as expected fatalities due to the forces of the vehicular accident. National statistics have been compiled for each mode from which fatal accident rates can be derived that are relevant for this study.

Conversions to fatal accident rates per shipment mile were made as follows. Highway heavy truck fatal accidents per vehicle mile have been previously reported in the literature, as have manifest train fatal accident rates per train mile. Derivation of a dedicated train fatal accident rate was made by assuming that the average manifest train consist is 70 cars and that a dedicated train consist would contain 4 cars. Published barge fatal accident rates are reported on a per ton-mile basis. Based on conversations with a barge carrier, it was concluded that the average dry cargo consist contains 15 barges, each carrying 1,500 tons. Conversion to a fatal accident rate per barge-mile was made using this information. All fatal accident rates were subsequently converted to a per-kilometer basis.

Discussion of Radtran 4 Results

The aforementioned approach represents application of a hybrid tool to assist in forming technical judgments. Consequently, its usefulness depends on the quality of data and relevance of assumptions.

Uncertainties are inherent in radiological risk prediction, especially for the low exposure levels associated with projected spent nuclear fuel transportation and the potential accidents associated with its transport. Health effects (primarily related to cancer) from exposures to low doses of radiation do not appear for several years, and predictions are made using conservative estimates based on observed health effects resulting from exposures to much higher radiation doses at much higher rates. Using risk assessment models does not reduce these uncertainties since the output is dependent on the input data and assumptions.

Using models that systematically represent the transport of spent nuclear fuel and activities associated with that operation, however, does provide a means for conducting a consistent comparison of the quantifiable factors and associated risks among different modes and routes for representative origin and destination pairs. Therefore, although the absolute effect of different factors on the levels of radiation doses for a given mode or route may be subject to question, the case study represents a valid framework for examining dependencies and variabilities of the primary factors and their relative relationship to public safety.

Some of the key modeling assumptions contained within Radtran 4 that may significantly impact the results of these analyses are listed below. No attempt was made to change these assumptions because no basis exists for justifying such changes. They can be subjected to sensitivity analysis to gauge their importance to estimation of overall risk values.

- Dedicated rail contains a Radtran 4 default exposure factor of 0.01; for manifest rail this exposure factor is 0.16. This factor is used to represent the exposure time and distance for the inspection crew risk calculation and is calculated as the sum across all of the exposure time divided by exposure distance. Highway and water modes were assigned the manifest rail factor (0.16) for inspection crew risk.

- Stop dose is calculated differently between modes. The rail model is based on the suburban population density (719 persons/km^2) over a 400-meter radius area. The other modes use a specified number of people exposed at a specified average distance.

- The rail stop model uses a shielding factor (0.1) while the other modes do not. This effectively reduces the rail stop risk by one order of magnitude.

- The highway model includes pedestrian exposure for urban areas. Rail and water modes do not calculate any pedestrian exposure.

- The water mode uses an exposure band from 200 meters to 1000 meters while rail and highway use an exposure band of 30 meters to 800 meters to measure surrounding population exposure.

As indicated above, Radtran 4 requires a large amount of information to perform a single analysis. The effect of variations of this data is difficult to determine without performing detailed sensitivity analyses on each variable.

Although Radtran 4 includes a sensitivity evaluation for the incident-free risk calculations, this evaluation is performed on a link basis for the route-specific option. No overall sensitivity is performed for the route. This means that as the factors that affect incident-free exposure are varied for a single link; only the change to the risk associated to that link is determined. Therefore, use of this information for this study is limited. A previous study, however, has assessed sensitivities of the Radtran model for a highway routing analysis.

When ranked by importance, the parameters having an influence of greater than 1 person-rem for incident-free risk were exposure distance at stops, dose rate conversion factor (K_0, which is a calculated factor based on the physical size of the container), the transport index (TI), number of packages per shipment, number of shipments per year and distance traveled. Of the factors listed, the exposure distance at stops for this study was constant within mode; K_0 and TI were constant throughout; and number of packages per shipment and number of shipments per year were assumed to be one for all cases. The length of travel was the only factor that varied with each analysis.

The sensitivity of radiological accident risk calculations to changes in input parameter values was analyzed for the following critical parameter groups: fractions of travel, accident rates, severity fractions, and release fractions. Parameters with large associated uncertainties were allowed to vary from the base case values by two orders of magnitude or more. Based on the results of the sensitivity study, it was concluded that no single parameter or parameter group dominates radiological accident risk. Each of the parameter groups were determined to be significant contributors to overall radiological accident risk. Increases in these parameters, however, produced disproportionately smaller increases in overall risk. It can be inferred, therefore, that the results of the Radtran 4 model are stable across wide ranges of input parameter values.

Although the results of the sensitivity study cannot be applied directly to the primary factors being evaluated in the case analyses, they do give some indication of inherently stable tendencies within the Radtran 4 modeling environment.

Presentation of Case Study Factor and Risk Values

Table G-4 presents summary case study values for both primary factors and radiological and non-radiological risks. This information is organized by shipping pair and mode. The significance of this table is that it demonstrates that relevant information on primary factors can be collected by mode and route, these factors can be applied to a risk assessment methodology, and the overall impacts to safety can be quantitatively measured.

The cases are organized by mode in Table G-5, where component and overall risk values are presented for incident-free and radiological accident risk, respectively. This information substantiates that risk values also vary considerably by O/D pair, mode, and route, possibly due to variations in primary factor values. This table also lends itself to some meaningful conclusions concerning the relative magnitudes of risk associated with various shipment characteristics. For example, incident-free risk tends to dominate the overall radiological risk associated with spent nuclear fuel shipments. In most instances, incident-free risk is much larger than radiological accident risk.

Table G-4. Summary case study factor and risk values.

O/D Pair	Mode	Independent Variables: Length (km)	Population Density (per/km^2)	Avg. No. of Crew	Average Speed (km/hr)	Accident Rate (acc./km)	Average Response Dist. (km)	Non-Rad Risk: No. of Fatalities	Incident Free Risk: Total (person-rem)	Rad. Accident Risk: Total (person-rem)
1	W	193.28	31.20	10.00	9.32	9.57E-06	894.00	2.64E-05	2.86E-03	4.32E-04
	H	171.39	98.05	2.00	37.80	9.98E-07	883.34	5.32E-06	2.19E-02	1.05E-04
	H	190.85	119.01	2.00	39.20	6.65E-07	885.23	5.93E-06	2.05E-02	1.01E-04
	H	227.07	24.39	2.00	36.24	8.50E-07	850.68	7.05E-06	2.80E-02	1.49E-05
	D	189.09	93.71	5.00	6.05	3.73E-06	899.03	2.35E-04	9.98E-03	4.48E-04
	M	189.09	93.71	2.00	2.49	3.73E-06	899.03	1.29E-05	4.20E-02	4.48E-04
2	W	190.86	0.47	10.00	9.51	3.11E-07	359.86	2.61E-05	2.15E-03	2.15E-07
	H	297.37	200.39	2.00	39.00	1.12E-06	322.62	9.24E-06	4.71E-02	9.83E-04
	H	391.03	60.37	2.00	35.14	1.15E-06	323.48	1.21E-05	6.42E-02	1.32E-04
	H	357.39	92.06	2.00	37.04	8.95E-07	328.82	1.11E-05	5.49E-02	2.03E-04
	D	292.09	391.93	5.00	7.07	3.73E-07	319.57	3.63E-04	2.44E-02	2.89E-03
	M	292.09	391.93	2.00	2.97	3.73E-07	319.57	2.00E-05	5.90E-02	2.89E-03
3	W	759.11	358.19	10.00	9.57	6.56E-06	291.39	1.04E-04	2.97E-02	1.71E-03
	H	559.20	211.01	2.00	38.18	7.05E-07	345.48	1.74E-05	8.44E-02	6.27E-04
	H	610.38	53.35	2.00	39.72	4.69E-07	352.93	1.90E-05	8.11E-02	8.02E-05
	D	653.05	250.67	5.00	7.90	3.72E-07	337.75	8.12E-04	3.39E-02	4.14E-03
	M	653.05	250.67	2.00	3.52	3.72E-07	337.75	4.46E-05	1.15E-01	4.14E-03
4	W	806.26	27.78	10.00	9.09	7.59E-06	606.80	1.10E-04	4.10E-03	1.44E-03
	H	940.31	101.01	2.00	39.56	7.10E-07	580.19	2.92E-05	1.24E-01	4.23E-04
	H	1102.68	48.03	2.00	39.70	4.86E-07	579.01	3.43E-05	1.38E-01	1.83E-04
	H	1051.97	37.46	2.00	39.10	6.35E-07	590.39	3.27E-05	1.38E-01	1.35E-04
	D	1213.57	161.48	5.00	15.40	3.72E-07	544.82	1.51E-03	3.34E-02	4.95E-03
	M	1213.57	161.48	2.00	6.52	3.72E-07	544.82	8.30E-05	9.98E-02	4.95E-03
	D	1589.02	111.90	5.00	13.36	3.73E-07	444.29	1.97E-03	3.92E-02	4.49E-03
	M	1589.02	111.90	2.00	5.91	3.73E-07	444.29	1.09E-04	1.42E-01	4.49E-03
5	WD	1263.18	6.80	9.75	9.19	8.89E-06	392.41	1.73E-04	6.01E-02	2.26E-03
	WM	1263.18	6.80	9.60	7.79	8.89E-06	392.41	1.73E-04	7.17E-02	2.26E-03
	H	788.93	37.37	2.00	39.20	6.64E-07	372.78	2.45E-05	1.08E-01	1.22E-04
	H	816.77	33.72	2.00	40.22	4.38E-07	387.68	2.54E-05	1.04E-01	9.22E-05
	H	863.61	18.49	2.00	37.20	8.16E-07	392.39	2.68E-05	1.25E-01	6.81E-05
	D	994.39	101.24	5.00	13.19	3.73E-07	391.41	1.24E-03	2.26E-02	1.96E-03
	M	994.39	101.24	2.00	5.96	3.73E-07	391.41	6.80E-05	8.58E-02	1.96E-03
	D	1008.07	99.59	5.00	12.05	3.73E-07	389.14	1.25E-03	2.73E-02	2.54E-03
	M	1008.07	99.59	2.00	5.50	3.73E-07	389.14	6.89E-05	9.90E-02	2.54E-03
6	WD	2498.12	129.22	8.53	10.68	2.35E-06	287.95	3.42E-04	1.08E-01	9.56E-03
	WM	2498.12	129.22	7.65	8.57	2.35E-06	287.95	3.42E-04	1.45E-01	9.56E-03
	H	1478.51	13.05	2.00	37.06	1.08E-06	320.55	4.59E-05	2.03E-01	2.06E-04
	H	1924.73	43.55	2.00	39.81	5.40E-07	216.41	5.98E-05	2.33E-01	3.28E-04
	H	1583.44	10.03	2.00	36.27	9.86E-07	284.39	4.92E-05	2.21E-01	5.19E-05
	D	2217.78	57.58	5.00	19.99	3.73E-07	198.63	2.76E-03	3.27E-02	3.23E-03
	M	2217.78	57.58	2.00	9.25	3.73E-07	198.63	1.52E-04	1.13E-01	3.23E-03
	D	2522.58	170.53	5.00	17.92	3.73E-07	230.23	3.14E-03	6.05E-02	1.09E-02
	M	2522.58	170.53	2.00	8.40	3.73E-07	230.23	1.72E-04	1.65E-01	1.09E-02
7	WD	2556.50	35.58	9.47	9.72	7.64E-06	742.42	3.49E-04	7.89E-02	5.40E-03
	WM	2556.50	35.58	9.15	8.51	7.64E-06	742.42	3.49E-04	1.01E-01	5.40E-03
	H	1953.27	56.92	2.00	39.25	1.23E-06	588.14	6.07E-05	2.51E-01	1.51E-03
	H	2387.43	43.52	2.00	40.46	4.48E-07	664.11	7.42E-05	2.79E-01	3.27E-04
	H	2021.88	70.42	2.00	40.01	6.48E-07	771.70	6.28E-05	2.48E-01	5.96E-04
	D	2369.69	141.57	5.00	17.29	3.73E-07	728.70	2.94E-03	5.35E-02	8.48E-03
	M	2369.69	141.57	2.00	7.57	3.73E-07	728.70	1.62E-04	1.65E-01	8.48E-03
	D	2336.87	84.38	5.00	15.49	3.73E-07	517.00	2.90E-03	4.71E-02	4.98E-03
	M	2336.87	84.38	2.00	6.98	3.73E-07	517.00	1.60E-04	1.73E-01	4.98E-03
	D	2224.21	117.96	5.00	15.04	3.73E-07	661.65	2.76E-03	5.35E-02	6.64E-03
	M	2224.21	117.96	2.00	6.78	3.73E-07	661.65	1.52E-04	1.73E-01	6.64E-03

Table G-4. Summary case study factor and risk values (continued).

		Independent Variables						Non-Rad Risk	Incident Free Risk	Rad. Accident Risk
O/D Pair	Mode	Length (km)	Population Density (per/km^2)	Avg. No. of Crew	Average Speed (km/hr)	Accident Rate (acc./km)	Average Response Dist. (km)	No. of Fatalities	Total (person-rem)	Total (person-rem)
8	WD	5527.27	13.94	7.45	13.87	4.77E-06	379.06	7.56E-04	1.09E-01	4.60E-03
	WM	5527.27	13.94	5.92	10.41	4.77E-06	379.06	7.56E-04	1.82E-01	4.60E-03
	H	3741.48	47.18	2.00	40.50	5.37E-07	427.29	1.16E-04	4.30E-01	1.40E-03
	H	4579.94	9.86	2.00	38.12	8.52E-07	428.57	1.42E-04	5.62E-01	2.23E-04
	H	3683.59	69.51	2.00	40.53	5.65E-07	422.65	1.14E-04	4.30E-01	3.02E-03
	D	4077.32	106.58	5.00	15.93	3.73E-07	392.55	5.07E-03	8.86E-02	1.10E-02
	M	4077.32	106.58	2.00	7.55	3.73E-07	392.55	2.79E-04	2.96E-01	1.10E-02
	D	4207.19	94.04	5.00	15.71	3.73E-07	422.99	5.23E-03	8.77E-02	1.00E-02
	M	4207.19	94.04	2.00	7.43	3.73E-07	422.99	2.88E-04	3.06E-01	1.00E-02
	D	4255.15	82.03	5.00	15.34	3.74E-07	419.19	5.29E-03	8.65E-02	8.82E-03
	M	4255.15	82.03	2.00	7.26	3.74E-07	419.19	2.91E-04	3.13E-01	8.82E-03

Legend:

D - dedicated train (rail)
M - manifest train (rail)
H - highway
W - waterway
WD - intermodal - barge and dedicated train
WM - intermodal - barge and manifest train

Table G-5. Radtran 4 component and overall risks.

O/D Pair	Mode	Incident Free Risk (person-rem): Crew	Handlings	Off-Link	On-Link	Stop	Incident Free Risk: Total (person-rem)	Rad. Accident Risk (person-rem): Ground	Inhalation	Resus-pension	Cloudshine	Rad. Accident Risk: Total (person-rem)
1	H	1.00E-02	0.00E+00	6.95E-04	5.77E-03	5.46E-03	2.19E-02	5.67E-05	8.94E-06	3.90E-05	3.20E-09	1.05E-04
1	H	1.05E-02	0.00E+00	1.92E-04	3.71E-03	6.08E-03	2.05E-02	5.46E-05	8.61E-06	3.75E-05	3.08E-09	1.01E-04
1	H	1.46E-02	0.00E+00	1.67E-04	5.96E-03	7.24E-03	2.80E-02	8.07E-06	1.27E-06	5.55E-06	4.56E-10	1.49E-05
2	H	3.02E-02	0.00E+00	1.43E-03	5.99E-03	9.47E-03	4.71E-02	5.33E-04	8.40E-05	3.66E-04	3.01E-08	9.83E-04
2	H	4.02E-02	0.00E+00	7.92E-04	1.08E-02	1.25E-02	6.42E-02	7.17E-05	1.14E-05	4.93E-05	3.78E-09	1.32E-04
2	H	3.57E-02	0.00E+00	1.22E-03	6.63E-03	1.14E-02	5.49E-02	1.10E-04	1.74E-05	7.58E-05	6.22E-09	2.03E-04
3	H	5.32E-02	0.00E+00	2.63E-03	1.07E-02	1.79E-02	8.44E-02	3.40E-04	5.37E-05	2.34E-04	1.92E-08	6.27E-04
3	H	5.39E-02	0.00E+00	9.29E-04	6.91E-03	1.95E-02	8.11E-02	4.34E-05	6.85E-06	2.99E-05	2.46E-09	8.02E-05
4	H	7.93E-02	0.00E+00	7.29E-04	1.40E-02	3.00E-02	1.24E-01	2.29E-04	3.62E-05	1.58E-04	1.30E-08	4.23E-04
4	H	8.83E-02	0.00E+00	1.05E-03	1.37E-02	3.51E-02	1.38E-01	9.76E-05	1.54E-05	6.71E-05	5.51E-09	1.83E-04
4	H	8.71E-02	0.00E+00	6.73E-04	1.65E-02	3.35E-02	1.38E-01	7.29E-05	1.15E-05	5.01E-05	4.11E-09	1.35E-04
5	H	7.14E-02	0.00E+00	1.26E-03	9.69E-03	2.52E-02	1.08E-01	6.59E-05	1.04E-05	4.53E-05	3.73E-09	1.22E-04
5	H	7.08E-02	0.00E+00	1.09E-03	6.21E-03	2.60E-02	1.04E-01	4.99E-05	4.99E-05	3.44E-05	2.82E-09	9.22E-05
5	H	8.05E-02	0.00E+00	7.56E-04	1.66E-02	2.76E-02	1.25E-01	3.69E-05	5.82E-06	2.54E-05	2.09E-09	6.81E-05
6	H	1.21E-01	0.00E+00	9.89E-04	3.47E-02	4.71E-02	2.03E-01	1.12E-04	1.76E-05	7.68E-05	6.31E-09	2.06E-04
6	H	1.47E-01	0.00E+00	2.69E-03	2.12E-02	6.14E-02	2.33E-01	1.78E-04	2.80E-05	1.25E-04	1.00E-08	3.28E-04
6	H	1.31E-01	0.00E+00	6.70E-04	3.92E-02	5.05E-02	2.21E-01	2.81E-05	4.43E-06	1.93E-05	1.59E-09	5.19E-05
7	H	1.52E-01	0.00E+00	3.50E-03	3.39E-02	6.22E-02	2.51E-01	8.17E-04	1.29E-04	5.61E-04	4.61E-08	1.51E-03
7	H	1.76E-01	0.00E+00	2.31E-03	2.40E-02	7.60E-02	2.79E-01	1.77E-04	2.79E-05	1.22E-04	1.00E-08	3.27E-04
7	H	1.52E-01	0.00E+00	3.54E-03	2.79E-02	6.45E-02	2.48E-01	3.22E-04	1.07E-04	2.21E-04	1.82E-08	5.96E-04
8	H	2.70E-01	0.00E+00	5.19E-03	3.60E-02	1.19E-01	4.30E-01	7.56E-04	1.19E-04	5.20E-04	2.03E-08	1.40E-03
8	H	3.44E-01	0.00E+00	2.20E-03	7.11E-02	1.45E-01	5.62E-01	1.21E-04	1.91E-05	8.31E-05	6.82E-09	2.23E-04
8	H	2.72E-01	0.00E+00	4.28E-03	3.60E-02	1.17E-01	4.30E-01	1.28E-03	2.03E-04	8.84E-04	7.25E-08	3.02E-03
1	D	1.51E-03	0.00E+00	1.85E-03	9.60E-05	6.52E-03	9.98E-03	2.81E-04	3.12E-05	1.34E-04	1.67E-08	4.48E-04
2	D	1.55E-03	0.00E+00	9.00E-03	1.68E-04	1.36E-02	2.44E-02	1.82E-03	2.02E-04	8.69E-04	1.08E-07	2.89E-03
3	D	1.48E-03	0.00E+00	1.51E-02	3.33E-04	1.70E-02	3.39E-02	2.60E-03	2.90E-04	1.25E-03	1.54E-07	4.14E-03
4	D	2.34E-03	0.00E+00	1.65E-02	5.88E-04	1.40E-02	3.34E-02	3.11E-03	3.46E-04	1.49E-03	1.84E-07	4.95E-03
4	D	2.80E-03	0.00E+00	1.34E-02	6.27E-04	2.24E-02	3.92E-02	2.83E-03	3.13E-04	1.35E-03	1.67E-07	4.49E-03
5	D	1.72E-03	0.00E+00	6.76E-03	6.95E-04	1.34E-02	2.26E-02	1.23E-03	1.37E-04	5.88E-04	7.29E-08	1.96E-03
5	D	2.64E-03	0.00E+00	8.57E-03	7.65E-04	1.53E-02	2.73E-02	1.60E-03	1.77E-04	7.62E-04	9.45E-08	2.54E-03
6	D	3.25E-03	0.00E+00	1.17E-02	9.39E-04	1.69E-02	3.27E-02	2.03E-03	2.26E-04	9.69E-04	1.20E-07	3.23E-03
6	D	3.77E-03	0.00E+00	3.28E-02	1.05E-03	2.29E-02	6.05E-02	6.85E-03	7.59E-04	3.27E-03	4.05E-07	1.09E-02
7	D	3.21E-03	0.00E+00	2.60E-02	9.17E-04	2.34E-02	5.35E-02	5.33E-03	5.92E-04	2.55E-03	3.16E-07	8.48E-03
7	D	3.35E-03	0.00E+00	1.57E-02	9.14E-04	2.71E-02	4.71E-02	3.14E-03	3.48E-04	1.50E-03	1.86E-07	4.98E-03
7	D	3.97E-03	0.00E+00	2.34E-02	1.02E-03	2.51E-02	5.35E-02	4.17E-03	4.63E-04	1.99E-03	2.47E-07	6.64E-03
8	D	5.59E-03	0.00E+00	3.65E-02	1.85E-03	4.46E-02	8.86E-02	6.89E-03	7.64E-04	3.28E-03	4.08E-07	1.10E-02
8	D	5.32E-03	0.00E+00	3.37E-02	1.93E-03	4.67E-02	8.77E-02	6.29E-03	6.97E-04	3.00E-03	3.73E-07	1.00E-02
8	D	5.30E-03	0.00E+00	3.04E-02	1.98E-03	4.89E-02	8.65E-02	5.55E-03	6.17E-04	2.65E-03	3.28E-07	8.82E-03
1	M	2.10E-02	0.00E+00	2.09E-03	1.13E-04	1.87E-02	4.20E-02	2.81E-04	3.12E-05	1.34E-04	1.67E-08	4.48E-04
2	M	2.80E-02	0.00E+00	8.37E-03	1.83E-04	2.24E-02	5.90E-02	1.82E-03	2.02E-04	8.69E-04	1.08E-07	2.89E-03
3	M	5.62E-02	0.00E+00	1.64E-02	3.81E-04	4.20E-02	1.15E-01	2.60E-03	2.90E-04	1.25E-03	1.54E-07	4.14E-03
4	M	4.27E-02	0.00E+00	1.65E-02	5.88E-04	4.01E-02	9.98E-02	3.11E-03	3.46E-04	1.49E-03	1.84E-07	4.95E-03
4	M	7.05E-02	0.00E+00	1.12E-02	4.59E-04	6.00E-02	1.42E-01	2.83E-03	3.13E-04	1.35E-03	1.72E-07	4.49E-03
5	M	4.21E-02	0.00E+00	6.87E-03	7.97E-04	3.60E-02	8.56E-02	1.23E-03	1.37E-04	5.88E-04	7.29E-08	1.96E-03
5	M	4.95E-02	0.00E+00	8.61E-03	8.52E-04	4.00E-02	9.90E-02	1.60E-03	1.77E-04	7.62E-04	9.45E-08	2.54E-03
6	M	5.06E-02	0.00E+00	1.22E-02	8.89E-04	4.94E-02	1.13E-01	2.03E-03	2.26E-04	9.69E-04	1.20E-07	3.23E-03
6	M	7.15E-02	0.00E+00	2.91E-02	8.80E-04	6.34E-02	1.65E-01	6.85E-03	7.59E-04	3.27E-03	4.05E-07	1.09E-02
7	M	7.13E-02	0.00E+00	2.65E-02	9.36E-04	6.67E-02	1.65E-01	5.33E-03	5.92E-04	2.55E-03	3.16E-07	8.48E-03
7	M	8.49E-02	0.00E+00	1.46E-02	6.99E-04	7.32E-02	1.73E-01	3.14E-03	3.48E-04	1.50E-03	1.86E-07	4.98E-03
7	M	7.86E-02	0.00E+00	2.44E-02	1.20E-03	6.91E-02	1.73E-01	4.17E-03	4.63E-04	1.99E-03	2.47E-07	6.64E-03
8	M	1.42E-01	0.00E+00	3.61E-02	1.48E-03	1.17E-01	2.96E-01	6.89E-03	7.64E-04	3.28E-03	4.08E-07	1.10E-02
8	M	1.49E-01	0.00E+00	3.27E-02	1.60E-03	1.23E-01	3.06E-01	6.29E-03	6.97E-04	3.00E-03	3.73E-07	1.00E-02
8	M	1.56E-01	0.00E+00	2.85E-02	1.61E-03	1.27E-01	3.13E-01	5.55E-03	6.17E-04	2.65E-03	3.28E-07	8.82E-03

Table G-5. Radtran 4 component and overall risks (continued).

		Incident Free Risk (person-rem)					Incident Free Risk	Rad. Accident Risk (person-rem)				Rad. Accident Risk
O/D Pair	Mode	Crew	Handlings	Off-Link	On-Link	Stop	Total (person-rem)	Ground	Inhalation	Resus-pension	Cloudshine	Total (person-rem)
1	W	4.04E-04	0.00E+00	6.78E-04	0.00E+00	1.78E-03	2.86E-03	2.10E-04	4.16E-05	1.81E-04	1.49E-08	4.32E-04
2	W	4.05E-04	0.00E+00	1.01E-05	0.00E+00	1.74E-03	2.15E-03	1.04E-07	2.07E-08	9.01E-08	7.40E-12	2.15E-07
3	W	4.05E-04	0.00E+00	2.76E-02	0.00E+00	1.74E-03	2.97E-02	8.26E-04	1.64E-04	7.15E-04	5.88E-08	1.71E-03
4	W	4.04E-04	0.00E+00	1.85E-03	0.00E+00	1.84E-03	4.10E-03	6.95E-04	1.38E-04	6.02E-04	4.94E-08	1.44E-03
5	WD	1.77E-03	4.86E-02	8.72E-04	1.43E-05	8.85E-03	6.01E-02	1.36E-03	1.70E-04	7.28E-04	8.53E-08	2.26E-03
6	WD	2.24E-03	4.86E-02	4.17E-02	6.22E-04	1.53E-02	1.08E-01	5.90E-03	6.90E-04	2.96E-03	3.56E-07	9.56E-03
7	WD	1.93E-03	4.86E-02	7.96E-03	9.58E-05	2.03E-02	7.89E-02	3.09E-03	4.35E-04	1.88E-03	1.98E-07	5.40E-03
8	WD	4.67E-03	4.86E-02	6.70E-03	1.10E-03	4.81E-02	1.09E-01	2.70E-03	3.58E-04	1.54E-03	1.70E-07	4.60E-03
5	WM	7.41E-03	4.86E-02	9.78E-04	2.03E-05	1.47E-02	7.17E-02	1.36E-03	1.70E-04	7.28E-04	8.53E-08	2.26E-03
6	WM	2.22E-02	4.86E-02	4.37E-02	7.38E-04	2.96E-02	1.45E-01	5.90E-03	6.90E-04	2.96E-03	3.56E-07	9.56E-03
7	WM	1.45E-02	4.86E-02	8.02E-03	7.67E-05	2.93E-02	1.01E-01	3.09E-03	4.35E-04	1.88E-03	1.98E-07	5.40E-03
8	WM	4.42E-02	4.86E-02	6.18E-03	7.33E-04	8.28E-02	1.82E-01	2.70E-03	3.58E-04	1.54E-03	1.70E-07	4.60E-03

Legend:

D - dedicated train (rail)
M - manifest train (rail)
H - highway
W - waterway
WD - intermodal - barge and dedicated train
WM - intermodal - barge and manifest train

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Appendix H

Model Estimation Using Case Study Analysis Results

Appendix H. Model Estimation Using Case Study Analysis Results

This appendix describes the use of the results of the case study database to statistically estimate model coefficients for the radiological risk models presented in Chapter 5. Model estimation was performed to develop a more detailed look at the relationship of primary factors to the risk components of public safety and to examine the sensitivity of risk components to individual factors and factor coefficients.

Modeling Approach

The case study database contains values for the independent variables (primary factors) and dependent variables (incident-free and radiological accident risks, respectively). Multiple linear regression analysis was considered as the initial basis for model estimation. A close examination of the terms contained in the incident-free model specification revealed, however, several terms with common factors (e.g., t_L) or terms that intuitively would be highly correlated. A subsequent correlation analysis of independent and dependent variables by mode confirmed this observation. The appearance of correlation of terms and factors typically leads to coefficient estimation problems due to multi-colinearity, resulting in estimates lacking statistical confidence and often possessing improper signs.

To address this concern, model estimation was designed around the use of single variable linear regression, estimating the coefficient of each term independently, using the primary factors comprising the term as the independent variables and the incident-free risk component as the dependent variable. This approach was also intuitively appealing since each term was derived independently to represent a specific incident-free risk component.

Evaluation of the quality of the regression analysis results was governed by the following criteria: (1) the overall goodness of fit, as measured by the adjusted R^2; (2) proper signs for the estimated coefficients; and (3) statistical confidence in each coefficient estimate, as measured by the t-statistic. A coefficient estimate was considered significant if the magnitude of the t-statistic exceeded the value corresponding to a 95 percent confidence that the coefficient value is significantly greater than zero. This value from the t-distribution varies by sample size and degrees of freedom, and therefore by mode in this case study. Corresponding t-values for each mode based on the case study sample size are:

Mode	Threshold t-Value
Highway	1.72
Manifest/Dedicated Rail	1.77
Waterway	2.92
Intermodal	1.94

Separate models were estimated by mode. The model results and statistical measures are presented for incident-free risk by mode in Tables H-1 through H-5, respectively. The radiological accident risk model results and statistical measures for each mode appear in Table H-6. These results are evaluated, in turn, in the following discussion.

Model Coefficient Derivations

This section presents the results of the regression analysis performed to estimate incident-free and radiological accident risk model coefficients, respectively.

Highway Incident-Free Risk

The highway incident-free risk model estimation results appear in Table H-1. Each coefficient, its corresponding value, t-statistic, and adjusted R^2 are presented. In addition, the mean value of the independent variable associated with each coefficient (consisting of primary factor values) is presented along with the estimated intercept (constant) and the mean value of the dependent variable (incident-free risk component).

Table H-1. Highway incident-free risk model.

Coefficient	Risk Component	Coefficient Value	t-Statistic	Adjusted R^2	Mean Value of Independent Variable	Constant	t-Statistic	Mean Value of Dependent Variable
a_1	off-link pop.	1.48×10^{-6}	8.92	.781	912.29 (pt_L)	3.48×10^{-4}	1.73	.002 (R_1)
a_2	on-link pop.	1.26×10^{-4}	11.32	.852	151.81 ($T\, t^2_L/L$)	7.76×10^{-4}	0.36	.020 (R_2)
a_3	crew	1.73×10^{-3}	54.41	.993	58.09 ($N_{crew} t_L$)	8.02×10^{-3}	3.29	.108 (R_3)
a_4	pop. at stops	3.18×10^{-5}	872.14	.999	1379.27 (L)	1.11×10^{-4}	1.67	.044 (R_4)

$$R_{IFE}\ (\text{highway}) = 1.48 \times 10^{-6}\, p\, t_L + 1.26 \times 10^{-4}\, T\, t^2_L/L + 1.73 \times 10^{-3}\, N_{crew}\, t_L + 3.18 \times 10^{-5}\, L + 9.26 \times 10^{-3}$$

All four coefficients in the highway incident-free risk model have the expected sign and are statistically significant. In addition, each coefficient and associated term is able to explain over 75 percent of the variation in its respective risk component. The component terms are grouped to present the overall derived expression for highway incident-free risk, R_{IFE} (highway), on the bottom of Table H-1.

In reviewing the mean values of the independent and dependent variables, a few items are notable. First, the independent variable associated with a_2 is large for highway (relative to other modes) because of the higher traffic densities of shared-facility users in highway operations. Similarly, the relatively low value for the a_3 associated term is due to smaller crew sizes for truck shipments. Finally, the overall contribution of a_1 and its term to highway incident-free risk is probably due to lower population densities along the interstates, where wider right-of-way is part of the facility design.

Manifest Rail Incident-Free Risk

Table H-2 presents the manifest rail incident-free model estimates and statistical information. As in the case of highway, all coefficient estimates exhibit the expected signs, are statistically significant and have high adjusted R^2. The resulting equation on the bottom of Table H-2 is a composite representation of manifest rail incident-free risks for spent nuclear fuel shipments.

Table H-2. Manifest rail incident-free risk model.

Coefficient	Risk Component	Coefficient Value	t-Statistic	Adjusted R^2	Mean Value of Independent Variable	Constant	t-Statistic	Mean Value of Dependent Variable
a_1	off-link	5.95×10^{-6}	15.26	.943	3128.24 (pt_L)	-3.58×10^{-4}	-0.26	.018 (R_1)
a_2	on-link	1.12×10^{-5}	12.97	.923	0.68 ($T\, t^2_L/L$)	7.93×10^{-5}	1.17	.001 (R_2)
a_3	crew	7.64×10^{-4}	8.06	.820	82.20 ($N_{crew} t_L$)	1.14×10^{-2}	1.26	.074 (R_3)
a_4	pop. at stops	2.49×10^{-5}	15.31	.943	2010.00 (L)	1.32×10^{-2}	3.39	.063 (R_4)

$$R_{IFE} \text{ (manifest rail)} = 5.95 \times 10^{-6}\, p\, t_L + 1.12 \times 10^{-5}\, T\, t^2_L/L + 7.64 \times 10^{-4}\, N_{crew}\, t_L + 2.49 \times 10^{-5}\, L + 2.43 \times 10^{-2}$$

One item of note is the relatively large value of the incident-free risk term associated with crew exposure in contrast to the dedicated rail model. This is due to the crew exposure factor of 0.16 used in Radtran 4 for manifest rail in contrast to a factor of 0.01 for dedicated rail. Although the other modes used a similar exposure factor of 0.16, the number of inspections is generally much smaller relative to rail operations.

Dedicated Rail Incident-Free Risk

The dedicated rail incident-free risk model estimate and associated statistics appear in Table H-3. Similar findings as reported previously apply here as well, in terms of model goodness of fit and coefficient signs and significance. The overall model as presented on the bottom of Table H-3 represents the entire derivation for dedicated rail incident-free risk for spent nuclear fuel shipments.

Waterway Incident-Free Risk

Because of the nature of waterborne transport, this model specification did not include on-link population exposure on the Gulf, Great Lakes, and oceans. A Boolean variable (0 for waterway; 1 otherwise) was included in the final model to account for this feature, thus removing the a_2 term from the waterway model specification. Results of the waterway incident-free risk model estimation appear in Table H-4. Model estimation statistics for off-link population risk are quite favorable, in contrast to an improper sign for the crew risk model coefficient and poor t-statistics for both crew risk and stop risk. The small sample size for waterway may be contributing to this effect. Fortunately, off-link population is the dominant independent variable in contributing toward the magnitude of waterway incident-free risk.

Table H-3. Dedicated rail incident-free risk model.

Coefficient	Risk Component	Coefficient Value	t-Statistic	Adjusted R^2	Mean Value of Independent Variable	Constant	t-Statistic	Mean Value of Dependent Variable
a_1	off-link	4.75×10^{-6}	28.15	.982	3965.50 (pt_L)	-1.02×10^{-4}	-0.13	.019 (R_1)
a_2	on-link	7.61×10^{-4}	25.27	.978	1.12 ($T\, t^2_L/L$)	7.16×10^{-5}	1.77	.001 (R_2)
a_3	crew	9.84×10^{-6}	18.76	.962	210.87 ($N_{crew} t_L$)	1.11×10^{-3}	8.45	.003 (R_3)
a_4	pop. at stops	9.13×10^{-6}	10.95	.895	2010.00 (L)	5.51×10^{-3}	2.75	.024 (R_4)

R_{IFE} (dedicated rail) $= 4.75 \times 10^{-6}\, p\, t_L + 7.61 \times 10^{-4}\, T\, t^2_L/L + 9.84 \times 10^{-6}\, N_{crew}\, t_L + 9.13 \times 10^{-6}\, L + 6.59 \times 10^{-3}$

Table H-4. Waterway incident-free risk model.

Coefficient	Risk Component	Coefficient Value	t-Statistic	Adjusted R^2	Mean Value of Independent Variable	Constant	t-Statistic	Mean Value of Dependent Variable
a_1	off-link	1.15×10^{-6}	67.08	.999	6701.16 (pt_L)	-1.64×10^{-4}	-0.79	.008 (R_1)
a_3	crew	-2.59×10^{-10}	-0.23	-.458	489.26 ($N_{crew} t_L$)	4.05×10^{-4}	0.24	.0004 (R^3)
a_4	pop. at stops	5.78×10^{-8}	0.65	-.240	487.38 (L)	1.75×10^{-3}	34.43	.002 (R_4)

R_{IFE} (waterway) $= 1.15 \times 10^{-6}\, p\, t_L + 2.59 \times 10^{-10}\, N_{crew}\, t_L + 5.78 \times 10^{-8}\, L + 1.99 \times 10^{-3}$

Intermodal Incident-Free Risk

As noted in Table H-5, all intermodal incident-free risk model coefficients have the expected sign; however, the a_2 and a_3 coefficient estimates are not statistically significant. This is of concern, given the relatively large contribution of a_3 and its associated term in the overall risk expression. The low value of the adjusted R_2 is a result of the fact that the on-link exposure only exists on the rail portions of the intermodal trip. Given the strong statistical strength of the other incident-free risk models and the a_5 (handling) term in the intermodal model, it may be preferable to model intermodal risks as the sum of the following three components: (1) originating mode, (2) intermodal transfer, using the a_5 handling term only, and (3) delivery mode.

Table H-5. Intermodal incident-free risk model.

Coefficient	Risk Component	Coefficient Value	t-Statistic	Adjusted R^2	Mean Value of Independent Variable	Constant	t-Statistic	Mean Value of Dependent Variable
a_1	off-link	1.95×10^{-6}	16.43	.975	8647.63 (pt_L)	-2.35×10^{-3}	-1.65	.015 (R_1)
a_2	on-link	2.86×10^{-5}	1.00	.001	13.59 ($T\, t^2_L/L$)	3.68×10^{-5}	0.09	.0004 (R_2)
a_3	crew	2.32×10^{-6}	0.18	-.160	1763.21 ($N_{crew} t_L$)	8.28×10^{-3}	0.36	.012 (R_3)
a_4	pop. at stops	1.29×10^{-5}	4.99	.773	2961.27 (L)	-7.22×10^{-3}	-0.83	.031 (R_4)
a_5	handling	4.90×10^{-2}	n/a	n/a	1.00 (H_1)	n/a	n/a	.049 (R_5)

R_{IFE} (intermodal) $= 1.95 \times 10^{-6}\, p\, t_L + 2.86 \times 10^{-5}\, T\, t^2_L 2/L + 2.32 \times 10^{-6}\, N_{crew}\, t_L + 1.29 \times 10^{-5}\, L + 4.77 \times 10^{-3}$

Radiological Accident Risk Models

All the radiological accident model estimation results are presented by mode in Table H-6. In all cases, the b_1 coefficient estimates have the expected sign. Coefficient statistical significance and overall goodness of fit as measured by the adjusted R^2 are also good, with the exception of the waterway radiological accident risk model. Fluctuations in population exposure as a function of width of the waterway and the small sample size are the likely causes of this problem. In general, however, the estimated equations appear to be useful predictors of radiological accident risk values for spent nuclear fuel shipments.

Table H-6. Radiological accident risk model.

Mode	Coefficient	Coefficient Value	t-Statistic	Adjusted R^2	Mean Value of Independent Variable	Constant	t-Statistic	Mean Value of Dependent Variable
Highway	b_1	1.55×10^{-2}	9.20	.792	.046 (pLS_A)	-2.35×10^{-4}	-2.32	.0005
	R_{ACE} (highway) = 1.55×10^{-2} ($p\ L\ S_A$) - 2.35×10^{-4}							
Manifest Rail	b_1	7.19×10^{-2}	11.41	.902	.089 (pLS_A)	-6.74×10^{-4}	-1.08	.006
	R_{ACE} (dedicated train) = 7.19×10^{-2} ($p\ L\ S_A$) - 6.74×10^{-4}							
Dedicated Rail	b_1	7.19×10^{-2}	11.41	.902	.089 (pLS_A)	-6.74×10^{-4}	-1.08	.006
	R_{ACE} (dedicated train) = 7.19×10^{-2} ($p\ L\ S_A$) - 6.74×10^{-4}							
Waterway	b_1	6.89×10^{-4}	1.50	.295	.503 (pLS_A)	5.49×10^{-4}	1.33	.001
	R_{ACE} (waterway) = 6.89×10^{-4} ($p\ L\ S_A$) + 5.49×10^{-4}							
Intermodal	b_1	8.41×10^{-3}	4.40	.724	.474 (pLS_A)	1.46×10^{-3}	1.40	.005
	R_{ACE} (intermodal) = 8.41×10^{-3} ($p\ L\ S_A$) + 1.46×10^{-3}							

Preliminary Model Validation

In addition to the statistical analyses presented in the previous section, preliminary model validation was performed by computing R_{IFE} and R_{ACE} for each mode using the estimated models and case study values as inputs, and comparing the results with the overall incident-free and radiological accident risk values computed directly from Radtran 4. This was considered a first stage validation because component, rather than overall, Radtran 4 risk values were used for estimating the model coefficients. A more independent validation approach would be to compare results using a second sample not utilized at all in the estimation process.

The differences between calculated and observed Radtran 4 overall incident-free and radiological accident risk values for each case are plotted by mode and risk model in Figures H-1 and H-2. (Care should be exercised in comparing across subfigures because of variations in the scales in which they are shown.) The results demonstrate a strong correlation between observed and predicted risk values in all cases.

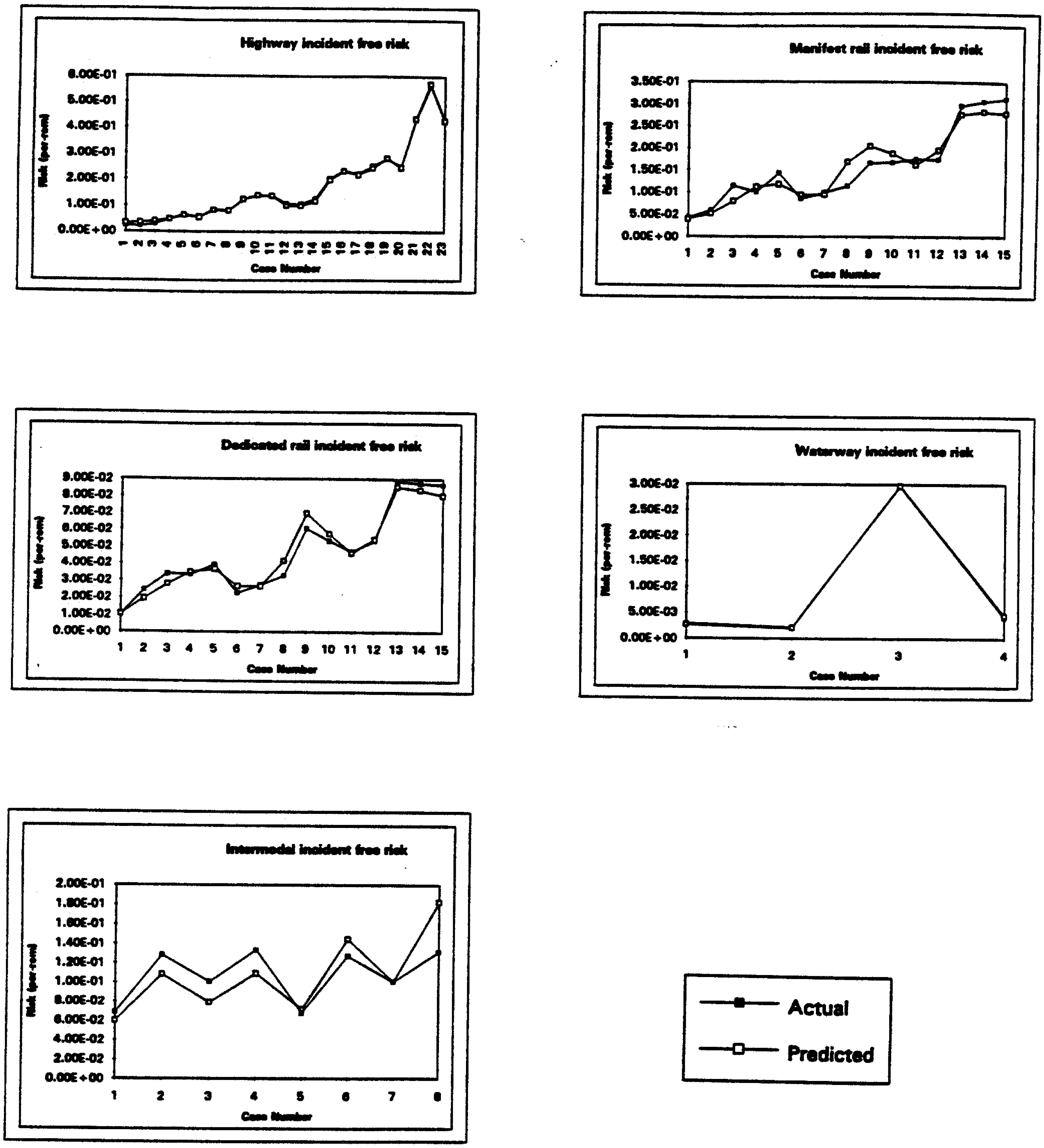

Figure H-1. Comparison of predicted and observed Radtran 4 incident-free risks.

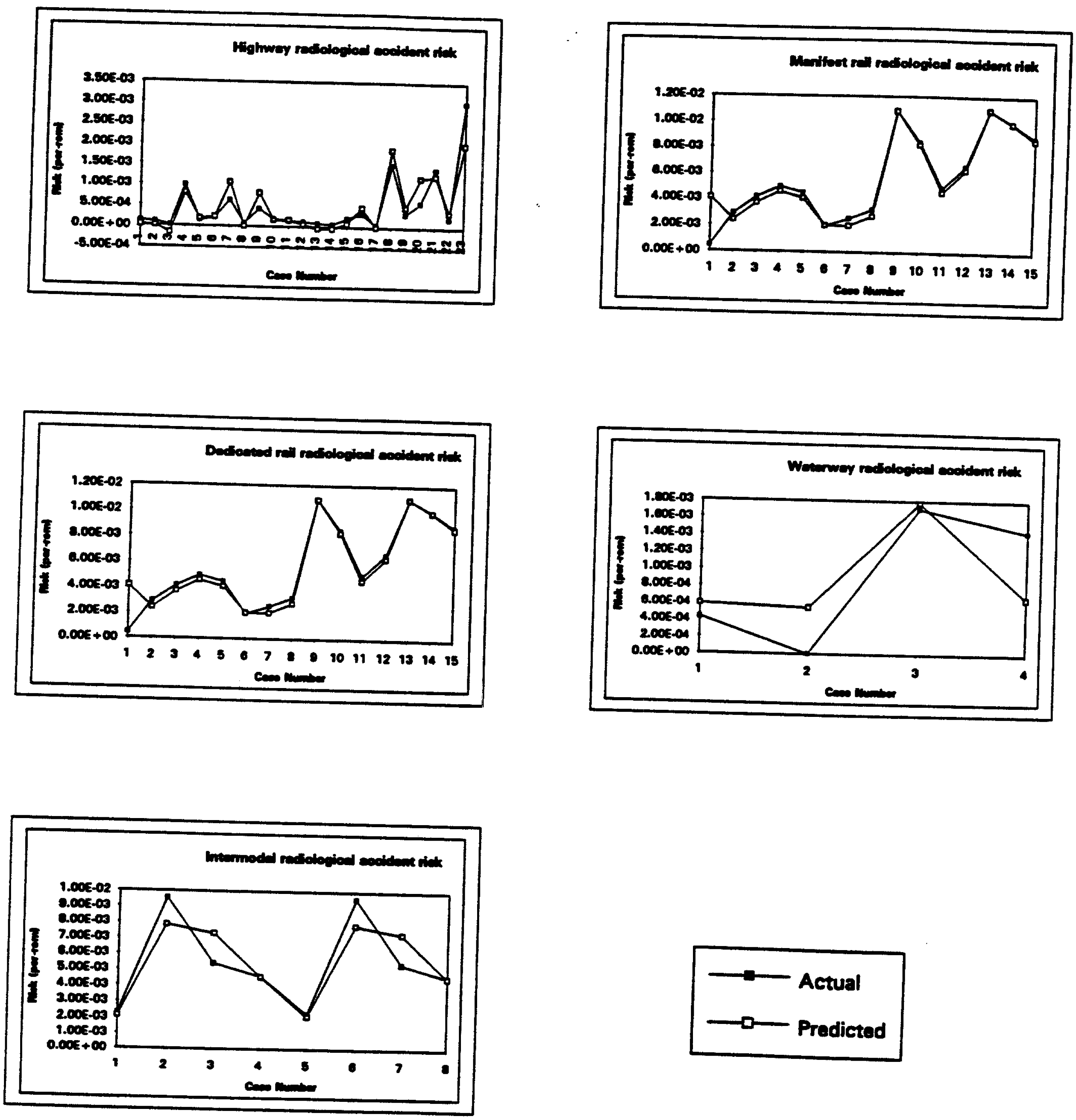

Figure H-2. Comparison of predicted and observed Radtran 4 radiological accident risks.